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ENVIRONMENTAL ASSESSMENT OF A WOOD-WASTE-FIRED INDUSTRIAL WATERTUBE BOILER

Volume I: Technical Results

by

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16. ABSTRACT The two-volume report gives results from field tests of a wood-waste-fired industrial watertube boiler. Two series of tests were performed: one firing dry (11% moisture) wood waste, and the other firing green (34% moisture) wood waste. Emission measurements included: continuous monitoring of flue gas emissions; source assessment sampling system (SASS) sampling of the flue gas with subsequent laboratory analysis of samples to give total flue gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and flue gas concentrations of 73 trace elements; Method 5 sampling for particulate; controlled condensation system sampling for SO2 and SO3; and grab sampling of boiler mechanical collector hopper ash for inorganic and organic composition determinations. Flue gas CO emissions from the boiler were quite high, attributed to the high excess air levels at which the unit operated. NOx emissions were comparable with both fuels (175-200 ppm). SO2 and SO3 levels were less than 10 ppm, in keeping with the low sulfur content of sboth fuels. Total organic emissions decreased from 60-135 mg/dscm firing dry wood to 2-65 mg/dscm firing green wood, in parallel with corresponding boiler CO emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Wood Wastes	Stationary Sources	11L
Water Tube Boilers	Particulate	13A
Flue Gases	Environmental Assessment	21B 06A
Assessments		14B
Particles		14G 07C
Sulfur Oxides		
Nitrogen Oxides		
Trace Elements		
Carbon Monoxide		
Organic Compounds		
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SECTION 1

INTRODUCTION

This report describes and presents results for a set of environmental assessment tests performed for the Industrial Environmental Research Laboratory/Research Triangle Park (IERL-RTP)* of EPA under the Combustion Modification Environmental Assessment (CMEA) program, EPA Contract No. 68-02-3188. The CMEA started in 1976 with a 3-year study the NO_x Control Technology Environmental Assessment (NO_x EA, EPA Contract No. 68-02-2160), having the following objectives:

- Identify potential multimedia environmental effects of stationary combustion sources and combustion modification technology
- Develop and document control application guidelines to minimize these effects
- Identify stationary source and combustion modification R&D priorities
- Disseminate program results to intended users

During the first year of the NO_x EA, data and methodologies for the environmental assessment were compiled. Furthermore, priorities for the schedule and level of effort for developing emission data for the various source/fuel/control combinations were identified. This effort revealed major

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*Now known as EPA's Air and Energy Engineering Research Laboratory (AEERL)

data gaps, particularly for noncriteria pollutants (organic emissions and trace elements) for virtually all combinations of stationary combustion sources and combustion modification techniques. Consequently, a series of seven environmental field test programs was undertaken to fill these data gaps. The results of these tests are documented in seven individual reports (References 1-1 through 1-7) and in the NO_x EA final report summarizing the entire 3-year effort (Reference 1-8).

The current CMEA program has, as major objectives, the continuation of multimedia environmental field tests initiated in the original NO_x EA program. These new tests, using standardized sampling and analytical procedures (Reference 1-9) are aimed at filling remaining data gaps and addressing the following priority needs:

- Advanced NO_x controls
- Alternate fuels
- Secondary sources
- EPA program data needs
  - -- Residential oil combustion
  - -- Wood firing in residential, commercial, and industrial sources
  - -- High interest emissions determination (e.g., listed and candidate hazardous air pollutant species)
- Nonsteady-state operations

In recent years, wood has experienced a revival as a primary or alternate source of energy for steam raising in industrial boilers and for space heating in the commercial and residential sector. The increase in the use of wood waste, originating primarily from the forest products

industries, has emerged due to increasing costs for the traditional fossil fuels, oil and gas. Wood has been projected to supply as much as 5 to 10 percent of the year 2000 national energy needs (References 1-10 and 1-11). Indeed, the U.S. Department of Energy is actively encouraging increased use of wood for industrial, as well as utility and residential energy requirements (Reference 1-12).

Emissions from wood combustion and associated air quality impacts have received attention since recent studies have suggested that wood combustion can produce significant emissions of potentially hazardous organic pollutants. In response to these concerns, a small industrial watertube boiler capable of burning wood waste, originating primarily from furniture manufacturing facilities, was selected for testing under the CMEA program. The objective of the tests were to quantify multimedia emissions from the boiler burning dry wood waste (low-moisture chips and sawdust) and green wood waste (high-moisture chips and sawdust). The data presented in this report quantify stack and collected flyash emissions and identify pollutants of potential concern using results from standardized sampling and analytical procedures (Reference 1-9).

Concurrent with this test program, one other wood-fired (firetube) boiler was tested to further evaluate the environmental impact of this fuel. Test results on this unit are documented in a separate report (Reference 1-13).

Table 1-1 lists all the tests performed in the CMEA program, outlining the source tested, fuel used, combustion modifications implemented and the level of sampling and analysis performed in each case. Results of these test programs are discussed in separate reports.

TABLE 1-1. COMPLETED TESTS DURING THE CURRENT PROGRAM

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Spark ignited natural gas-fired reciprocating internal combustion engine	Large bore, 6-cylinder, opposed piston, 186 kW (250 Bhp)/cyl, 900 rpm, Model 38TDS8-1/8	-- Baseline (pre-NSPS) -- Increased air-fuel ratio aimed at meeting proposed NSPS of 700 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Compression ignition diesel-fired reciprocating internal combustion engine	Large bore, 6-cylinder opposed piston, 261-kW (350 Bhp)/cyl, 900-rpm, Model 38TDD8-1/8	-- Baseline (pre-NSPS) -- Fuel injection retard aimed at meeting proposed NSPS of 600 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Low-NO_x residential condensing heating system furnished by Karlsons Blueburner Systems Ltd. of Canada	Residential hot water heater equipped with M.A.N. low-NO_x burner, 0.55 ml/s (0.5 gal/hr) firing capacity, condensing flue gas	Low-NO_x burner design by M.A.N.	Furnace exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Waste water	New test
Rocketdyne/EPA low-NO_x residential forced warm air furnace	Residential warm air furnace with modified high pressure burner and firebox, 0.83 ml/s (0.75 gal/hr) firing capacity	Low-NO_x burner design and integrated furnace system	Furnace exhaust: -- SASS -- Method 8 -- Controlled condensation -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel	New test

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Pulverized coal-fired utility boiler, Conesville station	400-MW tangentially fired; new NSPS design aimed at meeting 301 ng/J NO_x limit	ESP inlet and outlet, one test	ESP inlet and outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2 Coal Bottom ash ESP ash	Exxon Research and Engineering (ER&E) conducting corrosion tests
Nova Scotia Technical College industrial boiler	1.14 kg/s steam (9,000 lb/hr) firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with limestone injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, CO, NO Fuel	Envirocon performed particulate and sulfur emission tests
Adelphi University industrial boiler	1.89 kg/s steam (15,000 lb/hr) hot water firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with Na_2CO_3 injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, NO, CO Fuel	Adelphi University
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-oil (COM)	-- Baseline test only with COM	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Continuous O_2, CO_2, NO, TUHC, CO -- N_2O grab sample Fuel	PETC and General Electric (GE)

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
TOSCO Refinery vertical crude oil heater	2.54 Ml/day (16,000 bbl/day) natural draft process heater burning oil/refinery gas	-- Baseline -- Staged combustion using air injection lances	Heater outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO, CO_2, HC -- N_2O, grab sample Fuel oil Refinery gas	KVB coordinating the staged combustion operation and continuous emission monitoring
Mohawk-Getty Oil industrial boiler	8.21 kg/s steam (65,000 lb/hr) watertube burning mixture of refinery gas and residual oil	-- Baseline -- Ammonia injection using the noncatalytic Thermal DeNO$_x$ process	Economizer outlet: -- SASS -- Method 5, 17 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Ammonia emissions -- N_2O grab sample -- Continuous O_2, NO, CO, CO_2 Fuels (refinery gas and residual oil)	Mohawk-Getty Oil
Industrial boiler	2.52 kg/s steam (20,000 lb/hr) watertube burning woodwaste	-- Baseline (dry wood) -- Green wood	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO Fuel Flyash	North Carolina Department of Natural Resources, EPA IERL-RTP
Industrial boiler	3.16 kg/s steam (29,000 lb/hr) firetube with refractory firebox burning woodwaste	-- Baseline (dry wood)	Outlet of cyclone particulate collector: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO$_x$, CO Fuel Bottom ash	North Carolina Department of Natural Resources, EPA IERL-RTP

TABLE 1-1. (continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil equipped with MHI low-NO_x burner	-- Performance mapping -- Low NO_x operation	Steamer outlet -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2 -- N_2O grab sample Fuel	Getty Oil Company, CE-Natco
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-water (CWM)	-- Baseline test only with CWM	Boiler outlet -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Collector hopper ash	PETC and General Electric
Internal combustion engine -- nonselective NO_x catalyst	818-hp Waukesha engine equipped with DuPont NSER catalyst	-- Baseline -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- Grab sample N_2O -- Continuous O_2, CO_2, NO_x TUHC Fuel	Southern California Gas Company

Table 1-1. (concluded)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Industrial boiler	7.6 kg/s steam (60,000 lb/hr) watertube retrofit for coal water mixture firing	-- Baseline test with CWS -- 30-day emissions monitoring	Boiler outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, TUHC, SO_2 Fuel	EPRI, DuPont
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil, equipped with the EPA/EER low-NO_x burner	-- Low NO_x (with burner) -- 30-day emissions monitoring	Steamer outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Controlled condensation -- Anderson impactor -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC
Spark-ignited natural-gas-fired reciprocating internal combustion engine -- selective NO_x reduction catalyst	1,490-kW (2,000-hp) Ingersoll-Rand lean-burn engine equipped with Englehard SCR system	-- Low NO_x (with catalyst) -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- VOST -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, CO, NO, NO_x, NO_x+NH_3 Lube oil	Southern California Gas Company

[a]Acronyms used in the table: EERC, The Energy and Environmental Research Corporation; EPA IERL-RTP, The Environmental Protection Agency's Industrial Environmental Research Laboratory -- Research Triangle Park; EPRI, The Electric Power Research Institute; HC, hydrocarbons; NSCR, nonselective catalytic reduction; NSPS, new source performance standard; SASS, source assessment sampling system; SCR, selective catalytic reduction; TUHC, total unburned hydrocarbon; VOST, volatile organic sampling train

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SECTION 2

SOURCE DESCRIPTION AND OPERATION

The tests were performed on a Wickes stoker coal-fired industrial boiler modified to burn wood chips. The boiler, located at a furniture manufacturing plant, was selected because of its capability of burning both dry and green wood chips and because it was the site of an organic emissions evaluation program by the North Carolina Department of Natural Resources and Community Development (DNR). Results, from the CMEA test program on this unit provided additional data to the DNR program as well as duplicate data allowing for complete environmental assessment and data validity evaluation to the mutual benefit of both programs.

2.1 BOILER DESCRIPTION

The original industrial boiler was rated at 6.3 kg/s (50,000 lb/hr) of superheated steam at 1.7 MPa (250 psig) pressure and 338°C (640°F) temperature when burning bituminous coal. Table 2-1 summarizes the design specification of the original boiler. The boiler had been modified to burn waste wood chips from the plant's manufacturing facilities and from other local sources. Combustion of the wood waste entirely eliminated the plant's need for oil as a plant fuel resulting in substantial savings and decreased dependence on outside sources of energy.

Figure 2-1 illustrates the boiler configuration after the modifications were implemented to burn wood chips. Modifications consisted primarily of

TABLE 2-1. ORIGINAL BOILER DESIGN SPECIFICATIONS

Manufacturer	Wickes
Fuel feed	Stoker[a]
Boiler heating surface, m^2 (ft^2)	460 (4,950)
Furnace volume, m^3 (ft^3)	34.7 (1,225)
Economizer surface, m^2 (ft^2)	168 (1,810)
Maximum steam rating, kg/s (10^3 lb/hr)	6.3 (50)
Drum pressure, MPa (psig)	1.79 (260)
Steam temperature at S.H. outlet, °C (°F)	338 (640)
Steam pressure at S.H. outlet, MPa (psig)	1.73 (250)
Water temperature at econ. inlet, °C (°F)	105 (220)
Water temperature at econ. outlet, °C (°F)	156 (312)
Air temperature entering the boiler, °C (°F)	27 (82)
Air temperature leaving the boiler, °C (°F)	335 (635)
Furnace draft, Pa (in. H_2O)	-25 (-0.10)
Draft loss through boiler and S.H., Pa (in. H_2O)	453 (1.82)
Draft loss through collector, Pa (in. H_2O)	809 (3.25)
Draft loss through economizer, Pa (in. H_2O)	660 (2.65)
Excess air, percent	30
Boiler efficiency, percent	83.7

[a]Name plate on this unit did not specify coal feed mechanism. It is likely, however that a single retort underfeed stoker was in the original design.

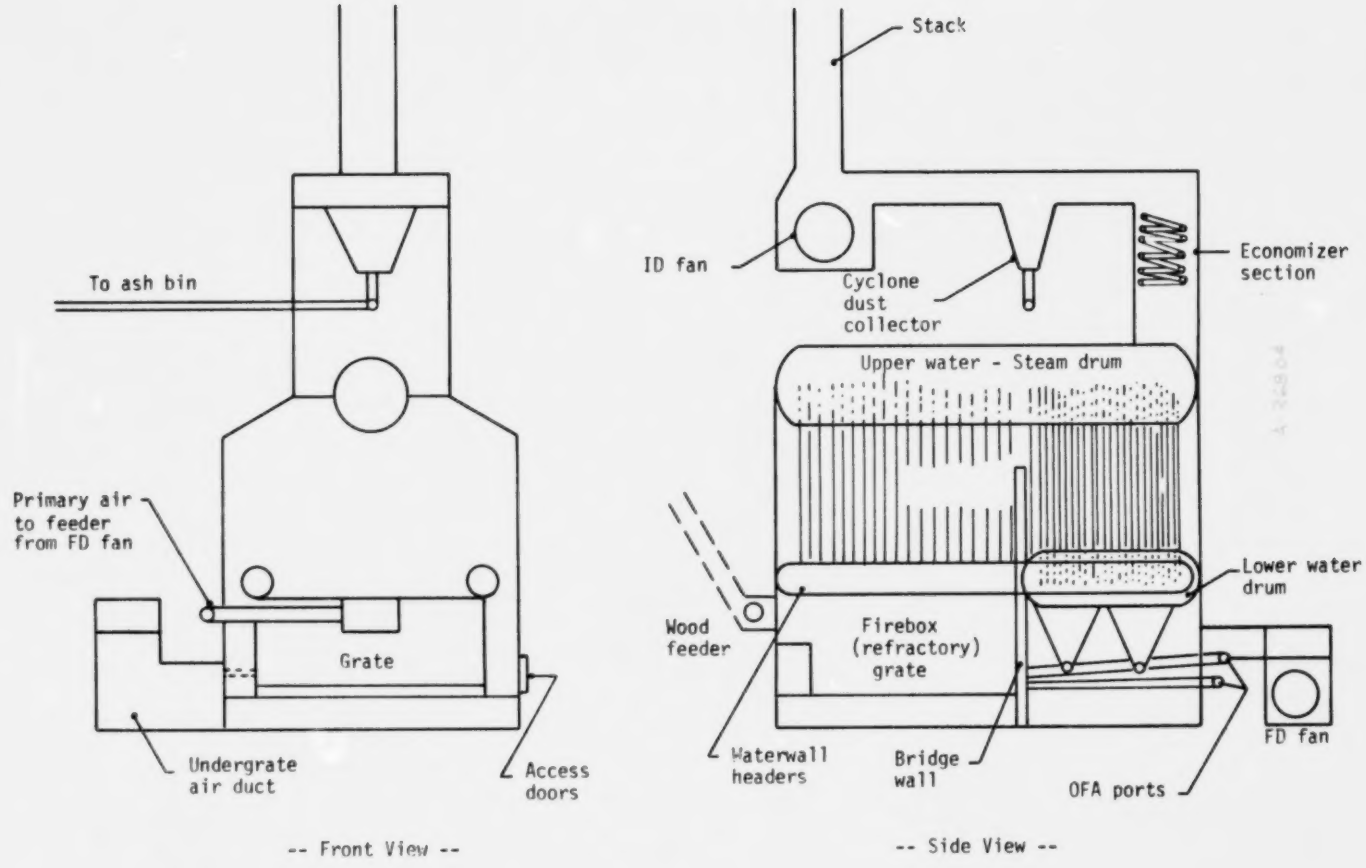


Figure 2-1. Schematic of coal-fired boiler converted to wood burning (not to scale).

raising the entire unit off its base by approximately 1.5m (5 ft) and installing a refractory-lined firebox equipped with a refractory hearth in place of the coal retort, and access ports for manual feed of dry wood for start up and ash removal. The wood chips and sawdust are fed to the boiler with a single helical wood screw feeder. Air from the forced draft fan is bled to the feeder to blow the wood into the firebox. The wood chips and sawdust ignite partially in suspension but the bulk of the combustion takes place on the grate. Two sets of air ports located approximately 0.45m (1.5 ft) above the grate provide overfire air injection from the rear and left side of the furnace. Orientation of these overfire air ports is skewed to promote a cyclonic flow in the firebox. Primary combustion air is injected under the hearth through 0.6-cm (0.25-in.) slots separating refractory bricks. Modification of the boiler for wood burning resulted in a decrease in steam capacity to about 3.2 kg/s (25,000 lb/hr), with lower superheater steam pressure and temperature.

2.2 BOILER OPERATION

The test program consisted of emission measurements when dry wood chip s and sawdust were burned (Test 1) and during combustion of green wood chips and sawdust (Test 2). Table 2-2 summarizes boiler operating data from available boiler room meters, and ultimate analyses of the fuels as fired in each test. Some important aspects of boiler operation during these tests can be summarized as follows.

Steam requirements in the furniture manufacturing plant are primarily for the drying kilns used to "cure" the wood. The total amount of steam needed for the kilns varies on a daily basis according to quantity of wood in the kiln and the ambient temperatures. Because of these varying conditions

TABLE 2-2. SUMMARY OF BOILER OPERATION AND FUEL

Test parameter	Test 1 (dry wood)		Test 2 (green wood)	
Boiler Operation:				
Steam load, kg/s (10^3 lb/hr)	1.8-2.2	(14-17)	0.88-1.4	(7-11)
Superheater steam temp., °C (°F)	227-274	(440-525)	271-296	(520-565)
Superheater steam press., MPa (psig)	1.00-1.17	(145-170)	1.13-1.30	(165-190)
Economizer inlet water temp., °C (°F)	63-69	(145-155)	66-69	(150-155)
Economizer outlet water temp., °C (°F)	121-133	(250-270)	113-121	(235-250)
Stack temperature after collect., °C (°F)	216-238	(420-460)	216-233	(420-450)
Bridgewall temperature, °C (°F)	354-483	(740-900)	538-594	(1,000-1,100)
Silo A (dry wood) feed, rpm	390-700		--	
Silo B (green wood) feed, rpm	--		500-620	
Furnace draft, Pa (in. H_2O)	0 to-100	(0 to-0.4)	-25 to-50	(-0.1 to-0.2)
Underfire air, Pa (in. H_2O)	75-200	(0.3-0.8)	125-175	(0.5-0.7)
Overfire air, kPa (in. H_2O)	5.5-5.6	(22.0-22.5)	5.5-5.6	(22.0-22.5)
Pressure before collector, Pa (in. H_2O)	450-600	(1.8-2.4)	320-500	(1.3-2.0)
Pressure after collector, kPa (in. H_2O)	0.5-1.0	(2.0-4.0)	0.55-0.75	(2.2-3.0)
Wood feed rate[a], kg/s (lb/hr)	0.29	(2,270)	0.54	(4,310)
Excess air, percent	387		213	
Boiler efficiency[b], percent	55.3		61.3	
Wood fuel ultimate analysis (Percent by weight as fired):				
Carbon	45.27		35.07	
Hydrogen	5.44		3.60	
Sulfur	0.04		0.02	
Nitrogen	0.12		0.10	
Oxygen	37.78		26.06	
Ash	0.33		1.29	
Moisture	11.02		33.85	
Higher heating value kJ/kg (Btu/lb)	17,900	(7,719)	13,300	(5,738)
Bulk density kg/m^3 (lb/ft^3)	233	(14.52)	192	(11.95)

[a]As-fired (wet) basis (a calculated value)
[b]Based on heat loss method

of kiln operation and ambient temperatures, combined with the absence of sufficient steam venting capability, boiler steam load could not be maintained constant during the test program. Table 2-2 indicates that the steam load during Test 2 was nearly half that of Test 1. The actual steam flowrates during each test, however, are probably not those indicated by the boiler-room meter since its operation was deemed unreliable by the plant personnel. In fact, steam feed rates calculated from the boiler efficiency (based on the heat loss method) and the wood flowrate would indicate feedrates of approximately 1.1 kg/s (8,400 lb/hr) for Test 1 and 1.6 kg/s (13,000 lb/hr) for Test 2.

Wood feed rates were not recorded by boiler room equipment. Feed rates listed in table 2-2 were instead calculated based on wood fuel ultimate analyses, volumetric stack gas flowrates measured with pitot tube readings and excess air levels measured with a continuous gas analyzer. Therefore, noted wood and steam flowrates should be considered approximate rather than actual.

Boiler efficiency, calculated using the ASME heat loss method, was 55.3 percent for Test 1 and 61.3 percent for Test 2. Table 2-3 summarizes the heat losses as a percent of the total heat input for each test. As indicated, the major heat loss was for the dry gas constituting about 70 and 50 percent of the total heat loss, respectively, for both tests. These high gas losses were due to the high excess air settings used in the operation of the boiler. Excess air was calculated to be about 390 percent for Test 1 and 210 percent for Test 2. The gain in efficiency during Test 2 was mostly due to the lower excess air level used. This gain was partially offset by a larger heat loss due to the higher moisture content of the green wood waste.

Table 2-3. BOILER THERMAL EFFICIENCY

Heat loss efficiency (percent)	Test 1 (dry wood)	Test 2 (green wood)
Heat loss due to dry gas	32.2	20.4
Heat loss due to moisture in the fuel	1.7	7.1
Heat loss to water from combustion of H_2 in fuel	7.8	6.8
Heat loss due to combustibles in the flyash[a]	0	0.9
Heat loss due to radiation	1.5	2.0
Unmeasured losses	1.5	1.5
Total loss	44.7	38.7
Efficiency (percent)	55.3	61.3

[a]Percent combustible in the flyash is discussed in section 3.4

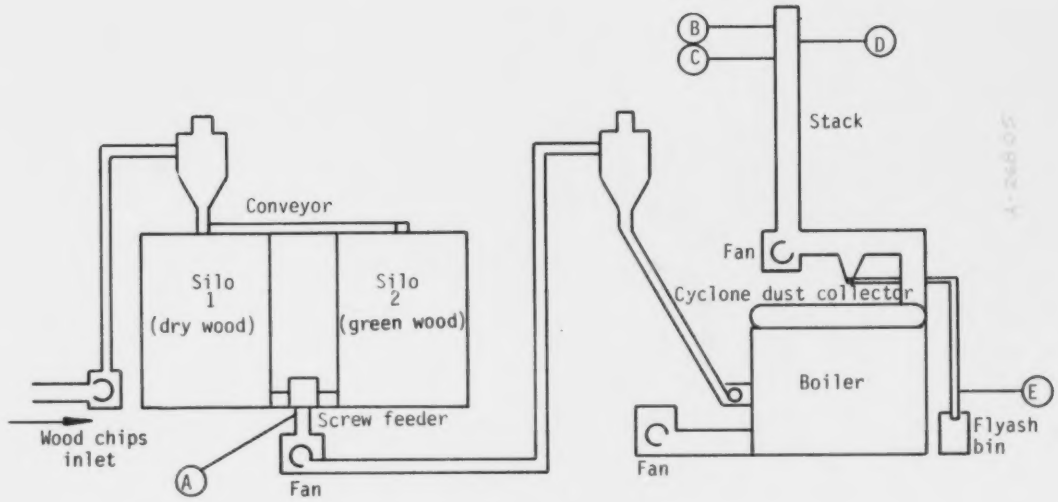
SECTION 3

EMISSION RESULTS

The objective of this test program was to measure flue gas emissions and pollutant concentrations in the flyash from the watertube boiler burning dry (low moisture) wood chips and sawdust (Test 1) and to duplicate measurements with the boiler burning green (high moisture) wood chips and sawdust (Test 2). Emission measurements were performed in cooperation with the North Carolina Department of Natural Resources and Community Development (DNR) whose team was onsite to perform polycylic organic matter (POM) emissions evaluation.

3.1 SAMPLING PROTOCOL

Figure 3-1 illustrates a schematic of the steam plant at the test facility highlighting the flow path of the dry and green wood waste and the sampling locations. Table 3-1 summarizes the samples taken, pollutants measured, measurement techniques used, and the test team performing the sampling and evaluation. As indicated, continuous monitoring of flue gas O_2, CO, and NO_x in the stack was performed by a team composed of EPA and GCA Corporation personnel. Both GCA and the DNR have drafted separate reports presenting the emission results (References 3-1 and 3-2). These results are discussed in this report to the extent that they aid in the evaluation of the emission data package and improve the validity of conclusions.



Sample Location	Type of Sample	Analyses	Test Team Member
A -- Silos screen feeders	Grab sample -- Wood	Proximate and ultimate, trace elements	Acurex
B -- Stack	Gas sample -- Continuous monitors	NO_x, O_2, CO	EPA/GCA
C -- Stack	Grab sample -- Modified Method 5	Particulate, organics	DNR
D -- Stack	Grab sample -- Method 5, controlled condensation and grab sample for onsite gas chromatography	Particulate load and size, trace elements, organics, SO_2/SO_3, C_1 to C_6 hydrocarbons, and bioassay	Acurex
E -- Flyash bin chute	Grab sample -- Flyash from mechanical collector	Trace elements, anions, organics, bioassay, and radionuclides	Acurex

Figure 3-1. Sampling sites and analysis matrix.

TABLE 3-1. EMISSION MEASUREMENTS

Sample location	Sample/pollutants	Measurement techniques[a]	Test team
A	Wood fuel bulk composition	Ultimate analysis	Acurex
B	Flue gas/O_2, CO, NO_x	Continuous monitors	EPA/GCA[b]
C	Flue gas/particulate and POM	Modified Method 5 with organic sorbent	DNR[c]
D	Flue gas/gaseous hydrocarbons C_1 to C_6	Onsite gas chromatography	Acurex
	Flue gas/SO_2, SO_3	Controlled condensation system (CCS)	Acurex
	Flue gas/particulate mass	EPA Method 5	Acurex
	Flue gas/NO_x	EPA Method 7	Acurex
	Flue gas/volatile and condensable organic species, inorganic trace elements, and particle size distribution	Source assessment sampling system (SASS)	Acurex
E	Flyash/inorganic trace elements, and leachable anions	Grab sample	Acurex

[a]Measurement and analysis techniques used are discussed in detail in Appendix A

[b]A more detailed presentation of EPA/GCA results and measurement techniques is given in Reference 3-1

[c]A more detailed presentation of DNR results and measurement techniques is given in Reference 3-2

3.2 CRITERIA POLLUTANT AND OTHER VAPOR SPECIES EMISSIONS

Table 3-2 summarizes gaseous and particulate emissions measured during both tests. Continuous monitoring equipment, including a gas conditioning system, was used to measure O_2, CO, and NO_x. Flue gas O_2 was quite high during both tests, even for wood-fired boilers which normally operate with high O_2 levels. The excess air level for Test 1 was 387 percent, and for Test 2, 213 percent. Some of this excess air may have come from air leakage into the boiler or exhaust ducts since the unit was under slightly negative pressure, 0 to -100 Pa (0 to -0.4 in. H_2O). Still, the very high CO emissions from the unit for both tests confirm that the combustion zone was at very high excess air.

NO_x emissions, corrected to 3 percent O_2, averaged 175 ppm and 194 ppm for Test 1 and Test 2, respectively. These concentrations correspond to 108 ng/J (1.93 g/kg) and 123 ng/J (1.63 g/kg) as NO_2, respectively. Emissions per unit of fuel were lower for the second test, in part because of the lower heating value of the green wood. However, emission levels for both tests were higher than would be expected for a wood-fired industrial boiler as documented in AP-42 (Reference 3-3). CO emission results are of significance because of the extremely high levels measured. CO emissions averaged 3.69 mg/J (66 g/kg) for Test 1 and 1.08 mg/J (14.4 g/kg) for Test 2. High emissions of CO during wood combustion are often a result of poor air/fuel mixing, short combustion gas residence times in the furnace, and rapid combustion gas cooling. As noted above, excess air levels during these tests were quite high, leading to both short furnace residence times and rapid combustion gas cooling downstream of the bridgewall.

TABLE 3-2. CRITERIA AND OTHER GAS SPECIES EMISSIONS

Pollutant[a]	Test 1 (dry wood)			Test 2 (green wood)		
As measured by continuous gas analyzers:						
O_2, dry percent	15.8 to 17.5 (16.4)[b]			11.7 to 15.8 (13.9)		
NO_x, dry ppm	19 to 62 (45)			37 to 131 (78)		
CO, dry ppm	996 to 3,440 (2,440)			283 to 2,260 (988)		
	ppm[c]	ng/J[d]	g/kg[e]	ppm[c]	ng/J[d]	g/kg[e]
Corrected average gaseous emissions:						
NO_x[f]	175	108	1.93	194	123	1.63
CO	9,810	3,690	66.0	2,810	1,080	14.4
Solid particulate mass emissions:						
-- Method 5 solid	--	204	3.64	--	267	3.55
-- Method 5 condensable	--	16	0.29	--	4	0.05
-- Method 5 total	--	220	3.93	--	271	3.60
-- SASS solid	--	198	3.55	--	310	4.12

[a]Appendix A discusses continuous monitor analyses used, calibration gases, sample gas conditioning system, particulate sampling equipment and procedures
[b]Numbers in parentheses are arithmetic averages of time-interval readings
[c]Corrected to 3 percent O_2, dry
[d]On heat input basis as fired
[e]As-fired (wet) basis; dry wood waste was 11.02 percent moisture, green wood waste was 33.85 percent moisture
[f]As NO_2

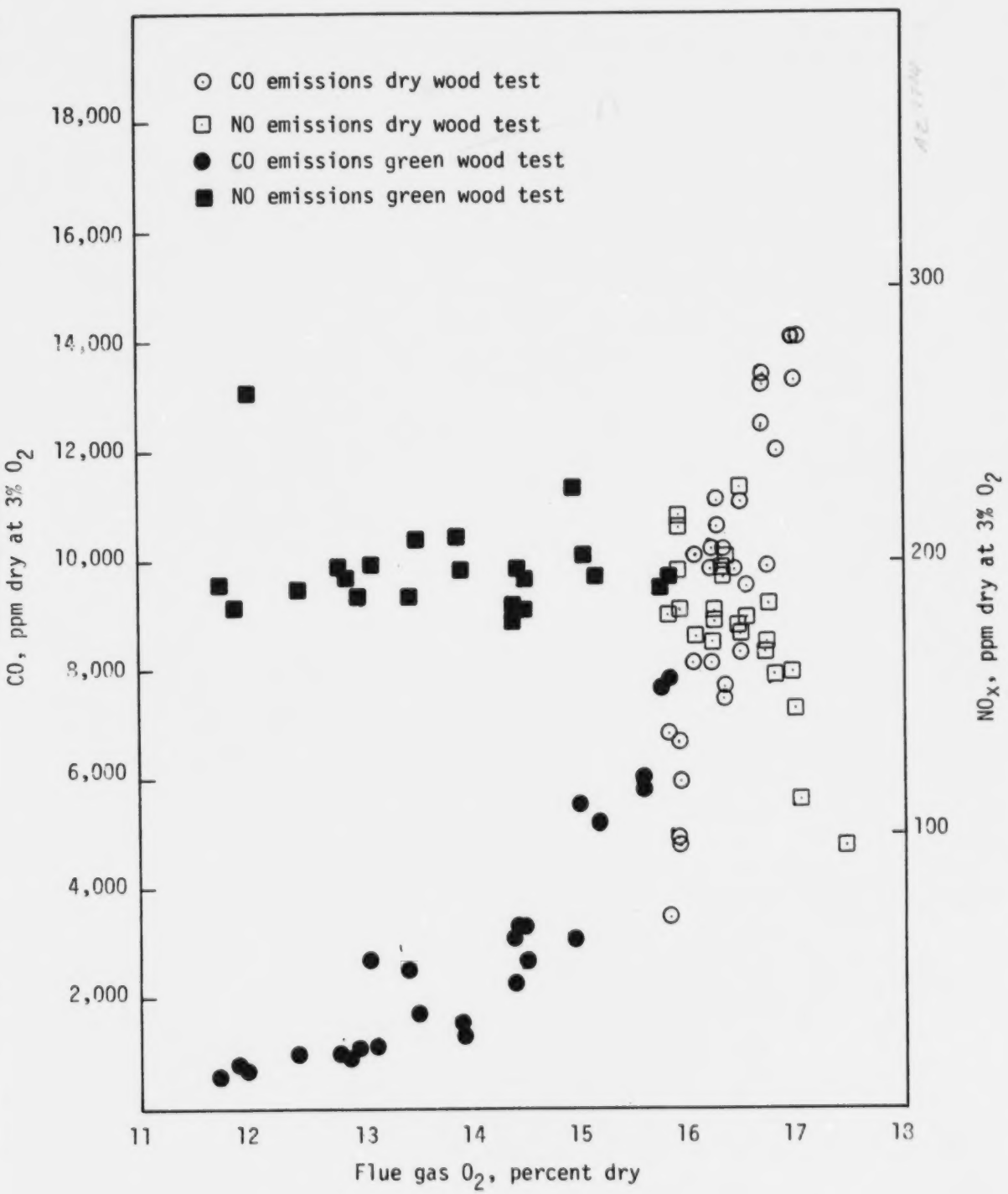


Figure 3-2. CO and NO_x versus O_2.

The effect of excess air (as measured by flue gas O_2) on CO emissions during these tests is shown in Figure 3-2 which compares the CO levels in the flue gas at various times with the corresponding flue gas O_2 reading. The figure shows that CO emissions (ppm dry at 3 percent O_2) varied from approximately 600 to nearly 8,000 ppm with flue gas O_2 varying from about 12 to 16 percent in Test 2, and from 5,000 to over 17,000 ppm with flue gas O_2 varying from 16 to 17.5 percent in Test 1. In fact, the CO versus O_2 curves for the two tests are contiguous. This suggests that, under conditions of these tests, the flame was being quenched by the large amount of excess air fired, and that the added effect of fuel moisture was insignificant compared to the effect of high excess air.

The NO_x emissions data, also shown in Figure 3-2, exhibit no definite variation with flue gas O_2 over the range in O_2 of 12 to 16 percent (Test 2). However, as flue gas O_2 increases from 16 to 17.5 percent (Test 1), corresponding NO_x emissions decrease. This behavior is consistent with flame quenching by high excess air.

SO_2 or SO_3 emissions in the flue gas were below a detection limit of 10 ppm using the controlled condensation system (CCS) with subsequent wet chemical analysis. This method normally has a detection limit of below 1 ppm. However, problems encountered in the laboratory titration of samples collected in the field (see Appendix A) resulted in an increased detection limit of 10 ppm. The fact that SO_2 and SO_3 emissions were below 10 ppm is not surprising in light of the low sulfur content of the wood. In fact, assuming 100 percent conversion of fuel sulfur to SO_2, maximum SO_2 concentrations would be only 12 ppm for both tests at stack conditions.

Particulate mass emissions (summarized in Table 3-2) obtained using two methods, the source assessment sampling system (SASS) and the multipoint EPA Method 5, are in relatively good agreement. Table 3-3 summarizes the Method 5 flue gas flowrate and particulate emissions measured by Acurex and the DNR field test teams. These independent measurements generally agree within 5 percent. Only the calculated particulate emissions rates (g/kg) for Test 1 differ by more than this. Table 3-4 summarizes particulate size distribution data obtained with the SASS equipment. These data show a definite shift in particle size distribution to larger sizes for the green wood fuel. However, based on data available in this study, the reasons for such a shift are not known.

3.3 TRACE ELEMENT EMISSIONS

Inorganic trace element concentrations were measured in the flue gas samples and flyash collected by the mechanical collector. Laboratory analyses included atomic absorption spectroscopy (AAS) for mercury, antimony, arsenic, and spark source mass spectrometry (SSMS) for 70 other elements. Once concentrations in the samples were determined by these analyses, trace element concentrations in both flue gas streams could be computed. These concentrations are presented in Appendix B. Trace element flowrates and mass balance estimates could not be calculated since the collected hopper ash flow rate was not measured.

Tables 3-5 and 3-6 give trace element concentrations in the wood fuel (wet, as fired) and the ash streams (particulate in two size ranges and the mechanical collector hopper ash) for Test 1 and Test 2, respectively. The data in the tables illustrate several interesting points. The first is that the trace element composition of the coarse (10 μm + 3 μm) particulate is

TABLE 3-3. COMPARATIVE PARTICULATE EMISSION RESULTS

Test	Sampling team	Flue gas flowrate dscm/s (dscf/min)	Solid particulate g/kg fuel[a] (lb/hr)
1 (Dry wood)	Acurex	6.37 (13,500)	3.64 (8.25)
	DNR[b]	6.51 (13,800)	2.87 (6.50)
2 (Green wood)	Acurex	5.99 (12,700)	3.55 (15.3)
	DNR[b]	6.28 (13,300)	3.45 (14.9)

[a]As-fired (wet) basis
[b]Average of two runs per test (Reference 3-2)

TABLE 3-4. PARTICLE SIZE DISTRIBUTION DATA, PERCENT TOTAL PARTICULATE (SASS) CATCH

Test	Particulate cut size			
	>10 μm (10-μm cyclone and probe)	10 to 3 μm (3-μm cyclone)	1 to 3 μm (1-μm cyclone)	<1 μm (filter)
1 (Dry wood)	30	23	15	32
2 (Green wood)	47	29	8	16

similar to that of the mechanical collector hopper ash, and the composition of both these ash samples is somewhat different from that of the fine (1 μm + filter) particulate. This suggests that, as expected, the mechanical collector is removing the coarse particulate from the flue gas more efficiently.

Secondly, the concentrations of most elements in the fine particulate are less than those in the coarse particulate. (Barium, iron, manganese, phosphorus, and potassium were the major constituents of both particulate fractions.) This is somewhat surprising in that the opposite occurs for efficiently operating coal-fired sources. In these an enrichment in the fine particulate is generally noted for several trace elements.

Comparing the data in Tables 3-5 and 3-6 shows that the trace element composition of the two fuels is very similar. Furthermore, the composition of the mechanical collector hopper ash for the two tests is also very similar.

In addition to trace element analyses of the solid mechanical collector hopper ash, analyses of a leachate prepared from the hopper ash of Test 1 were performed. The leachate was prepared following Level 1 procedures (Reference 3-4) which specify leaching a given weight of sample in four times this weight of water for 48 hr at 20°C. The leachate was then subjected to SSMS analysis for trace elements and analysis for certain leachable anions using wet chemical test kits.

Results of the leachate analysis are given in Table 3-7. Given the similarity between the solid composition of the mechanical collector hopper ash between Tests 1 and 2, leachate compositions are expected to be likewise similar.

TABLE 3-5. TRACE ELEMENT CONCENTRATIONS -- TEST 1 (DRY WOOD)

Element	Concentration in sample (μg/g)			
	Wood fuel	Particulate		Mechanical collector hopper ash
		10 μm + 3 μm	1 μm + filter	
Aluminum	>4.0	>1,000	--[a]	>1,000
Antimony	--	--	--	--
Arsenic	--	--	--	--
Barium	21	>1,000	>1,000	>1,000
Beryllium	--	<0.1	<0.1	0.3
Bismuth	--	--	<0.1	--
Boron	0.04	190	--	140
Bromine	0.4	8.0	--	6.0
Cadmium	0.03	0.70	0.20	1.0
Calcium	>100	>1,000	--	>1,000
Cerium	0.10	13	5.2	20
Cesium	0.06	0.60	0.20	0.60
Chlorine	10	680	92	870
Chromium	0.10	26	4.0	4.0
Cobalt	0.10	2.0	0.10	3.0
Copper	6.0	98	29	52
Dysprosium	--	2.0	0.20	--
Erbium	--	0.40	<0.10	--
Europium	--	0.50	0.10	4.0
Fluorine	0.6	>1,000	--	24
Gadolinium	--	1.0	0.3	2.0
Gallium	<0.01	7.0	0.69	5.0
Germanium	--	0.50	0.20	0.30
Hafnium	--	--	--	0.90
Holmium	--	0.50	0.10	--
Iodine	0.09	1.0	0.10	0.70
Iron	11	>1,000	>960	>1,000
Lanthanum	0.20	42	9.1	16
Lead	0.40	41	16	28
Lithium	0.03	0.30	--	5.0

[a]Dashes indicate trace element concentration was below the detection limit or had concentrations in the blank greater than in the sample. See Appendix B for detectability levels applicable to each stream.

TABLE 3-5. (concluded)

Element	Concentration in sample (μg/g)			
	Wood fuel	Particulate		Mechanical collector hopper ash
		10 μm + 3 μm	1 μm + filter	
Lutetium	--	0.10	<0.10	--
Magnesium	>100	>1,000	--	>1,000
Manganese	>45	>1,000	>990	>1,000
Mercury	<0.05	<0.83	<1.0	<0.05
Molybdenum	<0.01	10	0.39	2.0
Neodymium	<0.01	4.0	0.90	4.0
Nickel	0.08	17	3.5	60
Niobium	<0.01	5.0	--	4.0
Phosphorus	19	>1,000	>980	>1,000
Potassium	>54	>1,000	>980	>1,000
Praseodymium	0.02	2.0	0.90	4.0
Rubidium	0.40	79	59	130
Samarium	<0.02	5.0	0.80	3.0
Scandium	--	0.50	--	0.90
Selenium	0.01	0.50	3.0	5.0
Silicon	>100	>1,000	--	>1,000
Silver	0.20	4.0	3.9	--
Sodium	>11	>1,000	200	>1,000
Strontium	7.0	>1,000	>980	620
Sulfur	>27	>1,000	0.20	>1,000
Tantalum	--	--	--	--
Tellurium	0.03	0.30		0.50
Terbium	--	1.0	0.10	0.90
Thallium	0.03	--	--	--
Thorium	0.04	4.0	0.20	7.0
Thulium	--	0.10	<0.10	--
Tin	<0.01	0.4	0.10	0.50
Titanium	0.05	>1,000	--	>1,000
Tungsten	--	0.50	5.9	0.90
Uranium	0.03	1.0	<0.10	1.0
Vanadium	0.08	17	1.0	29
Ytterbium	--	0.90	0.01	--
Yttrium	0.04	7.0	2.7	11
Zinc	29	>1,000	390	410
Zirconium	0.07	6.0	--	10

[a]Dashes indicate trace element concentration was below the detection limit or had concentration in the blank greater than in the sample. See Appendix B for detectability levels applicable to each stream.

TABLE 3-6. TRACE ELEMENT CONCENTRATIONS -- TEST 2 (GREEN WOOD)

Element	Concentration in sample (μg/g)			
	Wood fuel	Particulate		Mechanical collector hopper ash
		10 μm + 3 μm	1 μm + filter	
Aluminum	>7.0	>1,000	--[a]	>1,000
Antimony	--	--	--	--
Arsenic	--	--	--	--
Barium	36	>1,000	>710	>1,000
Beryllium	<0.01	0.30	<0.07	<0.10
Bismuth	--	0.30	0.29	--
Boron	0.03	150	--	130
Bromine	0.07	14	--	29
Cadmium	0.10	3.0	0.14	1.0
Calcium	>100	>1,000	--	>1,000
Cerium	0.20	41	0.22	35
Cesium	0.03	1.0	<0.07	0.90
Chlorine	4.0	880	17	190
Chromium	0.04	8.0	0.79	38
Cobalt	0.50	3.0	--	3.0
Copper	3.0	84	14	45
Dysprosium	--	3.0	<0.07	3.0
Erbium	--	0.60	<0.07	0.60
Europium	--	0.70	<0.07	0.80
Fluorine	7.0	55	--	100
Gadolinium	--	2.0	<0.07	4.0
Gallium	0.10	5.0	0.50	11
Germanium	<0.01	0.40	0.07	0.80
Hafnium	0.08	2.0	<0.07	0.70
Holmium	--	0.80	<0.07	2.0
Iodine	0.04	1.0	0.07	3.0
Iron	>100	>1,000	>700	>1,000
Lanthanum	0.20	72	0.86	35
Lead	0.30	63	12	61
Lithium	0.05	22	0.36	2.0
Lutetium	--	0.20	<0.07	--
Magnesium	>100	>1,000	--	>1,000
Manganese	>76	>1,000	>35	>1,000
Mercury	<0.05	<1.1	<0.72	<0.05
Molybdenum	0.07	4.0	0.29	0.70

[a]Dashes indicate trace element concentration was below the detection limit or had concentration in the blank greater than concentration in the sample. See Appendix B for detectability levels applicable to each stream.

TABLE 3-6. (concluded)

Element	Concentration in sample (μg/g)			
	Wood fuel	Particulate		Mechanical collector hopper ash
		10 μm + 3 μm	1 μm + filter	
Neodymium	0.02	4.0	0.29	4.0
Nickel	0.30	6.0	2.5	14
Niobium	0.10	6.0	--	7.0
Phosphorus	>100	>1,000	>140	>1,000
Potassium	>92	>1,000	>39	>1,000
Praseodymium	0.04	8.0	0.07	6.0
Rubidium	3.0	300	22	290
Samarium	--	3.0	0.29	3.0
Scandium	0.01	0.90	--	0.80
Selenium	<0.02	2.0	0.72	4.0
Silicon	>100	>1,000	--	>1,000
Silver	0.08	<1.0	1.4	<0.2
Sodium	>19	>1,000	--	>1,000
Strontium	12	>1,000	56	860
Sulfur	>47	>1,000	>19	280
Tantalum	--	--	<0.07	--
Tellurium	0.05	--	--	0.4
Terbium	--	0.70	<0.07	1.0
Thallium	0.04	--	<0.07	--
Thorium	--	3.0	0.14	6.0
Thulium	--	0.20	<0.07	0.10
Tin	0.03	1.0	0.22	0.20
Titanium	9.0	>1,000	--	>1,000
Tungsten	--	--	0.30	0.70
Uranium	--	2.0	0.14	1.0
Vanadium	0.60	29	0.22	25
Ytterbium	--	2.0	<0.07	0.8
Yttrium	0.06	13	0.07	20
Zinc	22	460	430	390
Zirconium	0.50	22	0.72	39

[a]Dashes indicate trace elements concentration was below the detection limit or had concentration in the blank greater than concentration in the sample. See Appendix B for detectability levels applicable to each stream.

3.4 ORGANIC SPECIES EMISSIONS

Organic analyses were performed on flue gas samples and flyash according to the EPA Level 1 protocol (Reference 3-4) as outlined in Appendix A. Volatile gas phase organics having boiling points in the nominal C_1 to C_6 range of -160° to 100°C (-260° to 210°F) were measured by multiple analyses of flue gas samples using onsite gas chromatography. This procedure gives total volatile organics by boiling point range only. SASS and mechanical collector ash samples were extracted with methylene chloride in a Soxhlet apparatus. Volatile organic matter with boiling points in the nominal C_7 to C_{16} range of 100° to 300°C (210° to 570°F) were determined in the laboratory by total chromatographable organic (TCO) analysis of the organic module sorbent (XAD-2) and condensate sample extracts. Nonvolatile organic species having boiling points in the nominal $>C_{16}$ range of >300°C (570°F) were measured by gravimetric (GRAV) analysis of SASS sample extracts including filter and cyclone catches.

Infrared spectrometry (IR) was also performed on GRAV residues to identify organic functional groups. If total organic content in the sample exceeded 15 mg, as determined by TCO and GRAV procedures, further analyses by liquid chromatography (LC), with TCO, GRAV, and IR analyses of the fractions eluted from the column, were performed. Analyses of whole extract samples or LC fractions by low resolution mass spectrometry (LRMS) were performed if TCO and GRAV results indicated a stream organic emission concentration of greater than 0.5 mg/dscm for the flue gas. In addition, gas chromatography/mass spectrometry (GC/MS) analysis of total sample extracts was performed to identify specific polynuclear aromatic and other organic compounds (the

TABLE 3-7. TRACE ELEMENT AND LEACHABLE ANION CONCENTRATIONS IN AQUEOUS LEACHATE OF MECHANICAL COLLECTOR HOPPER ASH -- TEST 1 (DRY WOOD)

Element	Concentration (μg/ml)	Element	Concentration (μg/ml)
Aluminum	0.10	Lutetium	--
Antimony	--[a]	Magnesium	0.05
Arsenic	--	Manganese	0.005
Barium	>10	Mercury	--
Beryllium	--	Molybdenum	0.003
Bismuth	--	Neodymium	--
Boron	0.01	Nickel	0.02
Bromine	0.40	Niobium	--
Cadmium	0.002	Phosphorus	0.20
Calcium	>10	Platinum	<0.005
Cerium	0.002	Potassium	>10
Cesium	--	Praseodymium	--
Chlorine	>10	Rubidium	>10
Chromium	0.10	Samarium	--
Cobalt	<0.002	Scandium	<0.001
Copper	0.03	Selenium	--
Dysprosium	--	Silicon	>10
Erbium	0.06	Silver	--
Europium	--	Sodium	>10
Fluorine	4.0	Strontium	>10
Gadolinium	--	Sulfur	>10
Gallium	0.003	Tantalum	0.09
Germanium	<0.001	Tellurium	<0.008
Hafnium	--	Terbium	--
Holmium	0.80	Thallium	--
Iodine	0.05	Thorium	--
Iron	6.0	Thulium	--
Lanthanum	0.003	Tin	<0.009
Lead	0.08	Titanium	2.0
Lithium	0.01	Tungsten	0.090

[a]Dashes indicate trace element concentration was below the detection limit or had concentration in the blank greater than concentration in the sample. See Appendix B for detectability levels.

TABLE 3-7. (concluded)

Element	Concentration (μg/ml)	Element	Concentration (μg/ml)
Uranium	--[a]	Anions	
Vanadium	0.080		
Ytterbium	--	Fluoride	0.20
Yttrium	<0.001	Chloride	140
Zinc	0.02	Bromide	10
		Nitrate	25
Zirconium	0.002	Nitrite	59
		Sulfite	<2
		Sulfate	200
		Phosphate as P	0.040
		Ammonium as N	1.2

[a]Dashes indicate trace element concentration was below the detection limit or had concentration in the blank greater than concentration in the sample. See Appendix B for detectability levels.

semivolatile organic priority pollutants). A discussion of the analytical results follows.

3.4.1 C_1 to C_6 Hydrocarbon, TCO, and GRAV Analyses

Table 3-8 summarizes total organic emission results from the onsite GC, TCO, and GRAV analyses. The ranges in the emissions for volatile hydrocarbons shown reflect the multiple onsite GC analyses performed during each test. The dry wood test had total C_1 to C_6 hydrocarbon emissions significantly greater than those from green wood test. Table 3-8 also summarizes organic emission results from the TCO and GRAV analyses. These organic emissions results have been compromised somewhat due to the use, in these tests, of XAD-2 resin which had been inadvertently contaminated by acetone between resin preparation and eventual use. Thus, several acetone solvent contaminants and acetone polymerization products (chiefly an acetone dimer), all of relatively low molecular weight and in the TCO boiling point range, were introduced into the resin. This resulted in a high TCO blank for the XAD-2 resin for both tests. Table 3-9 shows the sample extract and field blank TCO values from both tests, and indicates the high, contaminated blank.

In an attempt to correct for the high blank, GC/MS analyses of the extracts were performed to identify and quantitate specific contaminant species in both the blank and sample extracts. Subtracting the amount of these contaminant species found in both sample and blank extracts from the TCO levels of each, allowed defining a corrected TCO value for both samples and the blank. These corrected levels are also shown in Table 3-9. TCO values listed in Table 3-8 reflect these corrected values. It should be

TABLE 3-8. SUMMARY OF TOTAL ORGANIC EMISSIONS IN THE GAS STREAM

Organic emissions	Test 1 (dry wood) mg/dscm	Test 1 (dry wood) g/kg fuel as fired	Test 2 (green wood) mg/dscm	Test 2 (green wood) g/kg fuel as fired
Volatile organics analyzed in the field by GC (nominal boiling point range)				
C_1	11 to 26	0.24 to 0.58	0.9 to 4.1	0.010 to 0.045
C_2	20 to 52	0.44 to 1.2	2.5 to 7.5	0.027 to 0.082
C_3	5.4	0.12	0 to 4.8	0 to 0.053
C_4	3.2 to 15	0.071 to 0.31	0 to 17	0 to 0.190
C_5	2.4 to 15	0.053 to 0.33	0 to <12	0 to <0.13
C_6	4.7 to 7.0	0.10 to 0.16	<5.5 to <31	<0.060 to <0.34
Total C_1 to C_6	47 to 120	1.0 to 2.7	3.4 to <76	0.037 to 0.84
Semivolatile organic material analyzed by TCO procedure				
XAD-2 cartridge	6.0	0.133	0.72	0.008
Organic module condensate	0.23	0.005	0.007	0.0001
Total C_7 to C_{16}	6.2	0.14	0.73	0.008
Nonvolatile organic material analyzed by GRAV procedure				
10 μm + 3 μm cyclones	<0.2	<0.004	<0.3	<0.003
Filter + 1 μm cyclone	<0.3	<0.007	<0.3	<0.003
XAD-2 cartridge	9.1	0.020	1.4	0.015
Organic module condensate	0.4	0.086	<0.1	<0.001
Total $>C_{16}$	9.5	0.21	1.4	0.015
Total organics	63 to 140	1.4 to 3.0	5.5 to <78	0.060 to <0.86

TABLE 3-9. XAD-2 EXTRACT TCO RESULTS

	Test 1 TCO (mg)	Test 2 TCO (mg)
Uncorrected		
Sample extract	250	140
Blank	120	120
Sample	130	20
Corrected		
Sample extract	130	20
Blank	0.64	0.64
Sample	130	19

TABLE 3-10. SUMMARY OF TOTAL ORGANIC CONTENT OF THE MECHANICAL COLLECTOR HOPPER ASH

Organics	Test 1 (dry wood) mg/kg ash	Test 2 (green wood) mg/kg ash
TCO	20	20
GRAV	700	650
Total organics	720	670

noted that all contamination consisted of TCO boiling range compounds so GRAV results should be unaffected.

Based on corrected values, emissions of TCO and GRAV compounds were also higher for the dry wood test. These results, combined with the C_1 to C_6 results, confirm the continuous monitoring measurements which indicated much higher combustible emissions for the dry wood test as evidenced by the higher CO concentrations in the flue gas during Test 1.

The combined (corrected) TCO and GRAV content of the XAD-2 sorbent extracts was 310 mg and 54 mg for Test 1 and Test 2, respectively. These total organic levels were sufficient to warrant further analysis by LC fractionation followed by TCO, GRAV, and IR analyses of the eluted fractions. Results of these analyses are presented in Sections 3.4.4 and 3.4.5.

Table 3-10 summarizes total organic content measured in the mechanical collector hopper ash samples collected during each test. On a concentration basis, mg/kg ash (ppm), both TCO and GRAV results indicate similar organic contents for the ash samples from both tests.

3.4.2 Infrared Spectra of Total Sample Extracts

IR spectrometry was used to identify organic functional groups present in the SASS and flyash samples. The results of the IR analysis of the total extract samples for both tests are summarized in Table 3-11. The spectra were weak for the 10 μm + 3 μm particulate extract for both tests, the filter + 1 μm particulate, and the organic module condensate for the dry wood test. Only the presence of aliphatic hydrocarbons was suggested in the spectra of the filter + 1 μm particulate extract for the green wood test and the mechanical collector hopper ash extracts for both tests. The spectrum for

TABLE 3-11. SUMMARY OF IR SPECTRA OF TOTAL SAMPLE EXTRACTS

Sample	Test 1 (dry wood)				Test 2 (green wood)			
	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present[b]	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present[b]
Combined 10 μm + 3 μm particulate	No peaks	--	--	--	No peaks	--	--	--
Filter blank	No peaks	--	--	--	No peaks	--	--	--
Filter + 1 μm particulate	No peaks	--	--	--	2,900	S	C-H stretch	Aliphatic hydrocarbons
XAD-2 blank	No peaks	--	--	--	No peaks	--	--	--
XAD-2 extract	3,600 to 3,000 2,900 2,820 1,790 1,600 1,440 1,180	S S S S W M M	O-H stretch C-H stretch C-H stretch C=O stretch C=C stretch C-H bend C-O stretch C-C stretch	Aliphatic hydrocarbons, carboxylic acids, esters, ketones, aldehydes, alcohols	2,900 2,820 1,710	S S M	C-H stretch C-H stretch C=O stretch	Aliphatic hydrocarbons, carboxylic acids, esters, ketones, aldehydes,
Organic module condensate	No peaks	--	--	--	3,680 to 3,200 3,100 to 2,200	S W	O-H stretch C-H stretch	Aliphatic hydrocarbons, alcohols
Mechanical collector hopper ash	2,900 2,820	S S	C-H stretch C-H stretch	Aliphatic hydrocarbons	2,900 2,820	S S	C-H stretch C-H stretch	Aliphatic hydrocarbons

[a]S: Strong, M: Moderate, W: Weak
[b]Possible compound categories present consistent with spectrum

the organic module condensate for the green wood test suggested that alcohols were possibly present.

The spectra for the XAD-2 extracts for both tests were the most complex. These suggested the possible presence of aliphatic hydrocarbons, carboxylic acids, and aldehydes for both tests. In addition, other oxygenates such as esters, ketones, or alcohols may have contributed to the IR spectrum of the XAD-2 extract for the dry wood test. Since IR spectra were obtained on the GRAV residues of the XAD-2 extract, the aforementioned resin contamination (TCO range compounds) would not have been expected to contribute to the spectra. This is confirmed by the weak blank extract spectrum.

3.4.3 GC/MS Analysis of Total Sample Extracts

Capillary column GC/MS analyses of the extracts of the flue gas samples collected by the SASS and the mechanical collector hopper ash were performed to detect and quantify specific POM and other organic compounds (the semivolatile organic priority pollutants). The compounds sought in the analyses and their respective detection limits are listed in Table 3-12. The results of the GC/MS analyses are summarized in Table 3-13. The POM and other compounds listed were detected in measurable quantities essentially only in the organic sorbent (XAD-2) extract (some phenol was measured in the organic module condensate (OMC) for Test 2). None of the compounds sought were detected in the mechanical collector hopper ash samples from either test.

Results indicate that naphthalene and phenanthrene were the major POM compounds in the flue gas during the dry wood test. For the green wood test, acenaphthylene and phenanthrene were the major POM compounds. Overall, total POM emissions were higher for Test 1 than for Test 2. The validity of this

TABLE 3-12. COMPOUNDS SOUGHT IN THE GC/MS AND THEIR DETECTION LIMITS (ng/μl INJECTED)

Acid Compounds			
2,4,6-trichlorophenol	5	2-nitrophenol	5
p-chloro-m-cresol	5	4-nitrophenol	20
2-chlorophenol	5	2,4-dinitrophenol	20
2,4-dichlorophenol	5	4,6-dinitro-o-cresol	20
2,4-dimethylphenol	5	pentachlorophenol	5
		phenol	1
Base Neutral Compounds			
1,2,4-trichlorobenzene	1	benzo(c)phenanthrene	40
1,2-dichlorobenzene	1	bis(2-chloroethoxy)methane	1
1,2-diphenylhydrazine (as azobenzene)	1	bis(2-chloroethyl)ether	1
		bis(2-chloroisopropyl)ether	1
1,3-dichlorobenzene	1	bis(2-ethylhexyl)phthalate	1
1,4-dichlorobenzene	1	butyl benzyl phthalate	1
2,4-dinitrotoluene	1	chrysene	1
2,6-dinitrotoluene	1	di-n-butyl phthalate	1
2-chloronaphthalene	1	di-n-octyl phthalate	1
3,3'-dichlorobenzidine	5	dibenzo(a,h)anthracene	5
3-methyl cholanthrene	40	dibenzo(c,g)carbazole	40
4-bromophenyl phenyl ether	1	diethyl phthalate	1
4-chlorophenyl phenyl ether	1	dimethyl phthalate	1
7,12-dimethyl benz(a)anthracene	40	fluoranthene	1
N-nitrosodi-n-propylamine	5	fluorene	1
N-nitrosodimethylamine	NA	hexachlorobenzene	1
N-nitrosodiphenylamine	1	hexachlorobutadiene	1
acenaphthene	1	hexachlorocyclopentadiene	1
acenaphthylene	1	hexachloroethane	1
anthracene	1	indeno(1,2,3-cd)pyrene	5
benzo(ghi)perylene	5	isophorone	1
benzidine	20	naphthalene	1
benzo(b)fluoranthene	1	nitrobenzene	1
benzo(k)fluoranthene	1	perylene	40
benzo(a)anthracene	1	phenanthrene	1
benzo(a)pyrene	1	pyrene	1

TABLE 3-13. POM AND OTHER ORGANIC SPECIES EMISSION SUMMARY -- TOTAL FLUE GAS

	Test 1 (dry wood)		Test 2 (green wood)	
Compound	µg/dscm	µg/kg fuel[a]	µg/dscm	µg/kg fuel[a]
Acenaphthene	--[b]	--	0.1	1.1
Acenaphthylene	0.5	11	5.2	57
Anthracene	--	--	0.2	2.2
Benzo/j+k/fluoranthenes	0.10	2.2	--	--
Chrysene	--	--	0.04	0.4
Fluoranthene	--	--	0.3	3.3
Fluorene	0.65	14	--	--
Naphthalene	4.5	100	--	--
Phenanthrene	7.0	160	2.0	22
Phenol	4.7	100	0.96	11
Pyrene	0.30	6.7	0.2	2.2
Other polynuclears	<0.05	<1.1	<0.04	<0.44

[a]kg fuel on wet basis
[b]Dashes indicate compound was not found to have concentration above the detection limits of 0.05 µg/dscm for Test 1 results and 0.04 µg/dscm for Test 2 results (more flue gas was sampled in the Test 2 SASS run resulting in a lower detection limit)

result is supported by the generally higher total organic and CO emission levels measured during the dry wood test.

Simultaneous POM emission tests performed by DNR offered an opportunity to validate results obtained in this program. Table 3-14 compares organic species detected in this test program to those obtained by DNR. The sampling equipment employed by DNR was based on the modified EPA Method 5 technique developed by Battelle-Columbus Laboratories (Reference 3-5). Collected samples were analyzed by a capillary column GC/flame ionization detector (FID) technique. As shown in Table 3-14, DNR recorded significantly higher naphthalene and pyrene emissions and significantly lower phenanthrene emissions than those determined with the SASS train. In addition, DNR detected low levels of benzo(a)pyrene and benz(a)anthracene, while SASS results do not show these compounds in concentrations exceeding detectability limits of the analysis. Emission levels for other species agree reasonably well; in most cases there was less than an order of magnitude difference between this program's and the DNR results.

3.4.4 Column Chromatography

The XAD-2 sample extracts for both tests were separated via LC fractionation. GRAV and TCO content were then obtained for each LC fraction. Results of these analyses are given in Tables 3-15 and 3-16. (TCO results in these tables are corrected for blank contamination as discussed in Section 3.4.1.) For Test 1 (Table 3-15), the LC fractionation indicates a relatively even distribution of organics in fractions 2 through 7.

For the green wood test (Table 3-16), most of the organics eluted in fractions 1, 6, and 7. Fraction 1 generally contains aliphatic hydrocarbons while fractions 6 and 7 generally contain polar oxygenates such as carboxylic

TABLE 3-14. COMPARISON OF POM EMISSION RESULTS FOR THE WOOD-FIRED BOILER TESTS (μg/dscm)

Species	Test 1 (dry wood)			Test 2 (green wood)		
	DNR		This study	DNR		This study
	Run 1	Run 2		Run 1	Run 2	
Naphthalene	51.7	63.9	4.5	21.9	44.8	--
Fluorene	--[a]	--	0.65	--	--	--
Phenanthrene	--	--	7.0	--	--	2.0
Anthracene	--	--	--	0.52	--	0.20
Fluoranthene	--	--	--	--	0.53	0.30
Pyrene	--	--	0.30	3.7	4.8	0.20
Benzo(a)anthracene	0.15	--	--	0.12	0.65	--
Chrysene	--	--	--	0.20	--	0.04
Benzo fluoranthenes	0.29	--	0.10	--	--	--
7,12-Dimethyl benz(a)anthracene	--	--	--	--	--	--
Benzo(a)pyrene	<0.21	--	--	0.10	--	--
Perylene	--	--	--	--	--	--
3-Methylcholanthrene	--	--	--	0.17	--	--
Indeno(1,2,3-cd)pyrene	--	--	--	0.51	--	--
Dibenz(a,h)anthracene	--	--	--	--	--	--
Benzo(g,h,i)perylene	--	--	--	--	--	--
Detection Limit	0.05	0.45	0.05	0.02	0.16	0.04

[a]Dashes denote less than detection limit

TABLE 3-15. GRAV AND TCO RESULTS OF COLUMN CHROMATOGRAPHY FOR TEST 1 (DRY WOOD) XAD-2 EXTRACT[a]

Fraction	TCO mg/dscm	GRAV mg/dscm	Total mg/dscm	Total mg/kg fuel as fired	Total ng/J heat input
LC1	0.056	0.15	0.21	4.7	0.26
LC2	0.27	<0.093	0.27	6.0	0.33
LC3	0.27	0.23	0.50	11	0.62
LC4	0.17	0.23	0.40	8.9	0.50
LC5	0.56	0.51	1.1	24	1.4
LC6	0.17	0.18	0.35	7.8	0.43
LC7	0.56	5.2	5.8	129	7.2
Total	2.1	6.5	8.6	190	11

[a]Results are based on the total organics recovered in each fraction corrected to total organics in the original sample

TABLE 3-16. GRAV AND TCO RESULTS OF COLUMN CHROMATOGRAPHY FOR TEST 2 (GREEN WOOD) XAD-2 EXTRACT[a]

Fraction	TCO mg/dscm	GRAV mg/dscm	Total mg/dscm	Total mg/kg fuel as fired	Total ng/J heat input
LC1	0.020	0.18	0.20	2.2	0.16
LC2	<0.001	0.067	0.07	0.8	0.06
LC3	<0.001	<0.037	<0.04	<0.4	<0.03
LC4	<0.001	0.092	0.09	1.0	0.07
LC5	<0.001	<0.037	<0.04	<0.4	<0.03
LC6	0.063	0.16	0.22	2.4	0.18
LC7	<0.007	0.26	0.26	2.8	0.21
Total	0.083	0.76	0.84	9.2	0.59

[a]Results are based on the total organics recovered in each fraction corrected to total organics in the original sample

acids, alcohols, esters, ketones, aldehydes, and phenols. With the exception of LC1 and LC6 which show approximately equal concentrations of organics for both tests, organics for Test 1 exceeded those of Test 2 in all fractions. Total organics were over an order of magnitude higher for the dry wood test than for the green wood test.

3.4.5 IR Analyses of Fractions From Column Chromatography

IR spectra were obtained on the GRAV residue of all sample fractions obtained from LC fractionation of the XAD-2 extracts. Table 3-17 summarizes these IR spectra results. Only the spectra for LC fraction 3 for both tests and LC fraction 7 for the dry wood test were strong enough to be interpreted. The presence of alcohols is suggested by the LC3 spectra for both tests. The spectrum for LC7 of the dry wood test extract is consistent with the possible presence of carboxylic acids, esters, alcohols, aldehydes and/or ketones.

The IR spectra of the LC fractions are consistent with those of the total extracts summarized in Table 3-11.

3.4.6. Low Resolution Mass Spectrometry Analysis of Total Extracts and LC Fractions

Tables 3-8 and 3-15 noted that several XAD-2 extract LC fractions and the OMC for the dry wood test, and the total XAD-2 extract for the green wood test had total organic content (TCO + GRAV) corresponding to emissions greater than 0.5 mg/dscm. In addition, Table 3-10 noted that the mechanical collector hopper ash extract for both tests had total organic content of greater than 1 mg/kg. Thus the green wood test total XAD-2 extracts, several combined XAD-2 extract LC fractions for the dry wood test, and the mechanical hopper ash extracts for both tests were subjected to low resolution mass spectrometry (LRMS) analysis via direct insertion probe. In addition,

TABLE 3-17. SUMMARY OF IR SPECTRA FOR LC FRACTIONS OF XAD-2 EXTRACT

Fraction	Test 1 (dry wood)				Test 2 (green wood)			
	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present[b]	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present[b]
LC1	No peaks	--	--	--	No peaks	--	--	--
LC2	No peaks	--	--	--	No peaks	--	--	--
LC3	3,450	S	O-H stretch	Alcohols, carboxylic acids	3,450	S	O-H stretch	Alcohols, carboxylic acids
LC4	No peaks	--	--	--	No peaks	--	--	--
LC5	No peaks	--	--	--	No peaks	--	--	--
LC6	No peaks	--	--	--	No peaks	--	--	--
LC7	3,230	M	O-H stretch C-H stretch	Carboxylic acids esters, alcohols, aldehydes, ketones	No peaks	--	--	--
	2,880	M	C-H stretch					
	2,810	M	C-H stretch					
	1,650	S	C-O stretch					
	1,190	S	C-O stretch C-O stretch					
LC7 Blank[c]	3,600 to 3,300	S	O-H stretch					

[a]S = strong, M = moderate
[b]Possible compound categories present consistent with spectra and LC fraction
[c]Spectra for all other fractions for the blank XAD-2 extract had no peaks

because the TCO contents of the dry wood test LC fractions and OMC were signficant, the selected combined fractions from this test were also subjected to LRMS analysis via batch inlet injection.

Table 3-18 presents the results of these analyses. As shown in the table, phenols, aldehydes, and heterocylic oxygen compounds (furan and benzofuran) were significant components of the organics collected by the XAD-2 sorbent and in the OMC for the dry wood test. Lower molecular weight (<216) polycyclic organic species were also present in the dry wood test XAD-2 extract, as well as the mechanical collector hopper ash extracts from both tests. Various oxygenated compound categories (ethers, carboxylic acids, and ketones) along with nitrogen containing organics (nitriles, amines, and heterocyclic nitrogen compounds) were identified in the OMC for the dry wood test.

In many cases, the direct insertion probe LRMS analyses identified different compound categories than the batch inlet analyses. However, the molecular weight of compounds identified in the batch inlet analyses was generally in the range that is poorly detected via direct insertion probe. Analyzing a method standard via direct insertion showed that compounds with molecular weight less than about 130 to 140 were lost (i.e., not recovered) to varying degrees. This is just the range identified by the batch inlet analyses.

As noted above, results for the XAD-2 extract and possibly for the OMC are compromised somewhat by the fact that the XAD-2 had been contaminated prior to use in the field. However, GC/MS analysis of both sample and field blank resin extracts showed the contaminant species to be acetone and acetone polymers (primarily the dimer) with small amounts of alkyl and alkenyl

TABLE 3-18. SUMMARY OF LRMS ANALYSES

Test	Sample	Direct insertion LRMS		Batch inlet LRMS	
		Compound category	Intensity[a]	Compound category	Intensity[a]
1 (dry wood)	XAD-2, LC2 + 3	Carboxylic acids	10	Polynuclear aromatics, MW <216 (naphthalene)	100
		Polynuclear aromatics, MW[b] <216	1		
	XAD-2, LC4 + 5	None found		Aldehydes, MW 106 to 120	100
				Aromatic hydrocarbons	10
				Phenols, MW 94 to 122	10
				Heterocyclic oxygen compounds, MW 118 to 146	10
	XAD-2, LC6 + 7	None found		Phenols, MW 94 to 122	100
				Heterocyclic oxygen compounds, MW 118 to 146	10
				Aldehydes, MW 84 to 124	10
				Aromatic hydrocarbons	10
	OMC	Ethers	100	Phenols, MW 94 to 136	100
		Nitriles	100	Heterocyclic oxygen compounds, MW 68 to 146	10
		Amines	100	Aldehydes, MW 96 to 120	10
		Heterocyclic sulfur compounds	100		
		Carboxylic acids	100		
		Halogenatic aliphatics	10		
		Aromatic hydrocarbons	10		
		Phenols	10		
		Ketones	10		
		Heterocyclic nitrogen compounds	10		
		Polynuclear aromatics, MW <216	1		
	Mechanical collector hopper ash	Polynuclear aromatics, MW <216	1		
2 (green wood)	XAD-2 total extract	None found		--[c]	--
	Mechanical collector hopper ash	Carboxylic acids	100	--	--
		Polynuclear aromatics, MW <216	10		

[a] 100 = Major component, 10 = minor component, 1 = trace component
[b] MW = Molecular weight
[c] -- = Analysis not performed

benzenes (ostensibly XAD-2 degradation products). Thus, the compound categories identified in the samples and noted in Table 3-18 should reflect species actually in the flue gas of the boiler sample (with the possible exception of the ketones and aromatic hydrocarbons in the OMC) and not caused by resin contamination.

3.4.7 Organic Emissions Summary

Tables 3-19 and 3-20 summarize organic emissions in the flue gas for Test 1 and 2, respectively. Inferences in Table 3-19 for Test 1 are based primarily on LRMS results as confirmed by IR spectra. Inferences in Table 3-20 for Test 2 are based entirely on IR spectra interpretations and must, therefore, be viewed with strict caution. Overall, organic flue gas emissions for Test 1 (dry wood) were about an order of magnitude greater than those for Test 2 (green wood). The organic content of the flue gas particulate corresponded to less than 0.3 mg/dscm for both tests. The organic content of the mechanical collector hopper ash was about 700 mg/kg ash for both tests.

3.5 RADIONUCLIDE EMISSIONS

Radiometric activities of the particulate catch from the SASS train and the flyash from the mechanical collector are presented in Table 3-21. The sum of alpha plus beta activities for the flue gas particulate, when converted to emission rates, corresponds to 770 pC_i/kg fuel for Test 1 and 760 pC_i/kg for Test 2. By comparison, the radionuclide emissions (excluding radon) calculated for a coal-fired powerplant range from 170 to 800 pC_i/kg of coal (Reference 3-6). Thus, emissions from the wood-fired unit are in the range of those from coal-fired powerplants.

TABLE 3-19. ORGANIC EXTRACT SUMMARY -- TEST 1 (DRY WOOD) XAD-2 AND OMC EXTRACTS

	LC1	LC2 + 3	LC4 + 5	LC6 + 7	OMC	Total
Total organics, mg	4.5	17	32	132	13	200
TCO, mg	1.2	12	16	16	4.9	50
GRAV, mg	3.3	5	16	116	8.0	150

	Assigned intensity -- mg/dscm					Total mg/dscm (mg/kg fuel)
Category	LC1	LC2 + 3	LC4 + 5	LC6 + 7	OMC	
Aliphatic hydrocarbons	100--0.21					0.21 (4.6)
Carboxylic acids		10--0.70			100-0.091	0.79 (17)
Polynuclear aromatic hydrocarbons, MW >216		1--0.07			1--0.001	0.0071 (0.16)
Aldehydes			100--1.2	10--0.5	10--0.009	1.8 (40)
Ethers					100--0.091	0.091 (2.0)
Nitriles					100--0.091	0.091 (2.0)
Amines					100--0.091	0.091 (2.0)
Heterocyclic sulfur compounds					100--0.091	0.091 (2.0)
Halogenated aliphatics					10--0.009	0.009 (0.2)
Aromatic hydrocarbons			10--0.1	10--0.5	10--0.009	0.61 (13)

TABLE 3-19. (concluded)

	LC1	LC2 + 3	LC4 + 5	LC6 + 7	OMC	Total mg/dscm (mg/kg fuel)
Phenols			10--0.1	100--4.7	100--0.091	4.8 (110)
Heterocyclic oxygen compounds			10--0.1	10--0.5	100--0.009	0.61 (13)
Ketones					10--0.009	0.009 (0.2)
Heterocyclic nitrogen compounds					10--0.009	0.009 (0.2)
Specific compounds -- mg/dscm						
Phenol						0.0047 (0.10)
Acenaphthalene						0.0005 (0.011)
Benzo/j+k/ fluoranthenes						0.0001 (0.002)
Fluorene						0.00065 (0.014)
Naphthalene						0.0045 (0.10)
Phenanthrene						0.0070 (0.16)
Pyrene						0.0003 (0.007)

TABLE 3-20. ORGANIC EXTRACT SUMMARY -- TEST 2 (GREEN WOOD) XAD-2 AND OMC EXTRACTS

	LC1	LC2 + 3	LC4 + 5	LC6 + 7	OMC	Total
Total organics, mg	5.4	1.8	2.5	13	0.2	23
TCO, mg	0.53	<0.04	<0.04	1.7	0.2	2.3
GRAV, mg	4.9	1.8	2.5	11.2	<3.0	20.4

Category[a]	Assigned intensity -- mg/dscm					Total, mg/dscm (mg/kg fuel)
	LC1	LC2 + 3 + 4 + 5 + 6 + 7			OMC	
Aliphatic hydrocarbons	100--0.20					0.20 (2.2)
Aldehydes			100--0.32		100--0.003	0.32 (3.5)
Carboxylic acids			100--0.32		100--0.003	0.32 (3.5)
	Specific compounds -- mg/dscm					
Phenol						0.00096 (0.011)
Acenaphthene						0.0001 (0.001)
Acenaphthylene						0.0052 (0.057)
Anthracene						0.0002 (0.002)
Chrysene						0.00004 (0.0004)
Fluoranthene						0.0003 (0.003)
Phenanthrene						0.0020 (0.022)
Pyrene						0.0002 (0.002)

[a]Summary of organic emissions are based on IR results primarily since LRMS did not show any organic groups

TABLE 3-21. RADIOMETRIC ACTIVITY OF SASS PARTICULATE AND COLLECTOR ASH SAMPLES

Test	Sample	Activity, pC_i/g Ash[a] Gross alpha	Gross beta
1 (dry wood)	Composite particulate from cyclones and filter catches[b]	16.8 ± 12.1	200.0 ± 18.5
	Mechanical collector hopper ash	17.6 ± 4.2	119.0 ± 38.0
2 (green wood)	Composite particulate from cyclones and filter catches[b]	21.7 ± 9.6	161.8 ± 30.5
	Mechanical collector hopper ash	15.6 ± 3.9	93.3 ± 35.0

[a]The ± values are the two sigma Poisson standard deviations of the counting error
[b]Corrected for filter blank

REFERENCES FOR SECTION 3

3-1. (Deleted.)

3-2. Wainwright, P.B., et al., "A POM Emissions Study for Industrial Wood-Fired Boilers," North Carolina Department of Natural Resources and Community Development, Raleigh, North Carolina, April 1982.

3-3. "Supplement No. 13 for Compilation of Air Pollutant Emission Factors, Third Edition," AP-42, NTIS PB83-126557, August 1982.

3-4. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

3-5. Jones, P. W., et al., "Measurement of Polycyclic Organic Materials and Other Hazardous Compounds in Stack Gases -- State of the Art," EPA-600/2-77-202, NTIS PB274013, October 1977.

3-6. "Radiological Impact Caused by Emissions of Radionuclides Into Air in the United States -- Preliminary Report," EPA-520/7-79-006, NTIS PB80-122336, August 1979.

SECTION 4

ENVIRONMENTAL ASSESSMENT

This section discusses the potential environmental impact of the wood-fired industrial boiler tested and discusses the results of the bioassay testing of flue gas and solid waste stream samples collected from the boiler burning both dry and green wood. The potential environmental impact is evaluated by comparing discharge stream species concentrations to occupational exposure guidelines or water quality criteria. These comparisons are done to rank species discharges for possible further consideration. Bioassay analyses were conducted as a more direct measure of the potential health and ecological effects of waste streams. Both these analyses are aimed at identifying problem areas and providing the basis for ranking of pollutant species and discharge streams for further consideration.

4.1 EMISSIONS ASSESSMENT

To obtain a measure of the potential significance of the discharge streams analyzed in this test program, discharge stream concentrations were compared to indices which reflect potential for adverse health effects. For the flue gas discharge, the indices used for comparison were occupational exposure guidelines. Two sources of such guidelines were used: time-weighted-average Threshold Limit Values (TLV's) defined by the American Conference of Governmental Industrial Hygenists (ACGIH) (Reference 4-1) and

8-hr time-weight-average exposure limits established by the Occupational Safety and Health Administration (OSHA) (Reference 4-2). For the mechanical collector hopper ash, the indices used were the health-based water quality criteria promulgated by EPA (Reference 4-3), compared to ash leachate concentrations. For recognized carcinogens, water quality criteria are defined corresponding to different levels of cancer risk in individuals consuming contaminated drinking water over a lifetime. The values associated with the 10^{-5} risk level (an increased lifetime cancer risk of 1 in 100,000) were used here.

The comparisons of discharge stream species concentrations to these potential adverse health indices were only performed to rank species discharge levels with respect to potential for adverse effects. Conclusions concerning absolute risk associated with the discharges evaluated were not, and should not be drawn. These evaluations are only presented to place different species dischages into perspective and to rank them for further consideration.

Table 4-1 lists those pollutant species emitted in the flue gas discharge stream at levels greater than 10 percent of their occupational exposure guideline for either test performed. Emissions of carbon monoxide and NO_x were over an order of magnitude higher than their respective occupational exposure guidelines, up to over two orders of magnitude for CO in Test 1. Silver, nickel, and phosphorus were emitted at levels exceeding their respective occupational exposure guidelines for both tests.

Table 4-2 lists the concentrations of those species in the mechanical hopper ash leachate from the dry wood test which exceeded their respective health-based water quality criteria. Only barium had a leachate

TABLE 4-1. FLUE GAS SPECIES EMITTED AT LEVELS EXCEEDING 10 PERCENT OF THEIR OCCUPATIONAL EXPOSURE GUIDELINES

Pollutant	Emitted concentrations (μg/dscm) Test 1 (dry wood)	Test 2 (green wood)	Occupational exposure guideline ($\mu g/m^3$)[a]
Carbon monoxide (CO)	2.8×10^6	1.3×10^6	5.5×10^4
Silver, Ag	790	14	10
NO_x	8.7×10^4	1.5×10^5	6,000
Nickel, Ni	120	290	100
Phosphorus, P	>160	>280	100
Barium, Ba	>160	>330	500
Potassium, K	>300	>1,300	2,000
Iron, Fe	>190	>470	1,000
Sodium, Na	>720	>370	2,000
Chromium, Cr	8.2	17	50
Copper, Cu	11	59	200
Lead, Pb	5.2	18	150
Cobalt, Co	5.6	0.79	50

[a]Threshold Limit Value (Reference 4-1)

TABLE 4-2. MECHANICAL COLLECTOR HOPPER ASH SPECIES WITH LEACHATE CONCENTRATIONS EXCEEDING A WATER QUALITY CRITERION

Species	Test 1 (dry wood) hopper ash leachate concentrations (μg/ml)	Water quality criterion (μg/ml)
Barium, Ba	>10	1.0
Chromium, Cr	0.10	0.050
Lead, Pb	0.080	0.050
Nickel, Ni	0.020	0.0134

concentration significantly greater than its water quality criterion. As noted in Section 3, leachate composition data were developed only for the mechanical collector hopper ash from the dry wood test (Test 1). However, Section 3 also noted that the trace element composition of the solid mechanical collector hopper ash for the green wood test (Test 2) was very similar. Thus, similar conclusions concerning its leachate composition would be expected.

4.2 BIOASSAY RESULTS

Bioassay tests were performed on the organic sorbent (XAD-2) extracts, particulate flyash collected by the SASS train, and the mechanical collector hopper ash. Bioassay results reported here are for both health and ecological effects test (Reference 4-4). A detailed description of the biological analyses performed is presented in Volume II (Data Supplement) of this report. The bioassay tests performed on the XAD-2 extracts were health effects tests only. These were:

- Ames assay, based on the property of Salmonella typhimurium mutants to revert due to exposure to various classes of mutagens
- Cytotoxicity assay (CHO) with mammalian cells in culture to measure cellular metabolic impairment and death resulting from exposure to soluble toxicants

In addition to the Ames test, health effects bioassay tests performed on the mechanical collector hopper ash and the particulate collected by the SASS included:

- The rabbit alveolar macrophage (RAM) cytotoxicity assay which gives a toxicity evaluation measured by the reduction in cell viability

and adenosine triphosphate content of the cultures after several hours exposure to the test material

- The whole ammial acute toxicity test in live rodents (WAT) to identify *in vivo* toxicity of samples

Table 4-3 summarizes the results from the Ames, CHO, RAM, and WAT assays. Overall, the results suggest that all samples, except the XAD-2 extracts, were of nondetectable to low toxicity and mutagenicity. The XAD-2 extracts for both tests showed high toxicity and mutagenicity. The XAD-2 extract for the dry wood test contained about an order of magnitude higher total organic content than the XAD-2 extract for the green wood test (mg/dscm basis). However, the relative contents of semivolatile organic priority pollutants, including POM species, were more comparable. If these latter are the components resulting in toxic and mutagenic responses, the fact that there were no differences in response between the tests is understandable.

Flyash samples from the mechanical collector hopper were also tested for acute toxicity to freshwater invertebrates (Daphnia magna), freshwater fish (fathead minnow, Pimephales promelas) and freshwater algae (Selenastrum capricornutum). Table 4-4 summarizes the results of these tests. Results of these assays suggest that the samples were of nondetectable to low toxicity.

4.3 SUMMARY

Comprehensive emissions characterization tests were performed on a watertube industrial boiler converted to burn wood waste. Two series of tests were performed: one with the boiler firing dry wood waste (11.02 percent moisture), and one with the boiler firing green wood waste (33.85 percent moisture). Flue gas NO_x, CO, and particulate emissions were measured (SO_2 and SO_3 were sampled for, but not detected). In addition, flue

TABLE 4-3. BIOASSAY RESULTS (HEALTH EFFECTS)

Test	Sample	Bioassay			
		Ames[a]	CHO[b]	RAM[b]	WAT[b]
1 (dry wood)	Combined particulate (cyclones and filter catches)	ND	--	--	--
	XAD-2 sorbent extract	H/M	H	--	--
	Flyash	ND	--	L/ND	ND
2 (green wood)	10 µm + 3 µm cyclone catches	ND	--	L/ND	
	1 µm cyclone and filter catches	ND	--	M	--
	XAD-2 sorbent extract	H	H	--	--
	Flyash	ND	--	ND	ND

[a]Mutagenicity test
[b]Toxicity test

ND -- Nondetectable
L -- Low
M -- Moderate
H -- High
-- Assay not performed

TABLE 4-4. BIOASSAY RESULTS (ECOLOGICAL EFFECTS)

Test	Sample	Aquatic organisms		
		Invertebrate[a]	Freshwater fish[b]	Freshwater algae[c]
1 (dry wood)	Flyash	ND/L	ND	L
2 (green wood)	Flyash	ND/L	--	L

[a]Daphnia magna
[b]Pimephales promelas
[c]Selenastrum capricornutum

ND -- Nondetectable toxicity
L -- Low toxicity
-- Assay not performed

gas emissions of 73 inorganic trace elements, total organics in three boiling point ranges, and POM's and selected other organic species were also measured. The mechanical collector hopper ash was also analyzed for trace element composition, total organic content, and leachable trace element and anion content.

CO emissions from the boiler were very high, averaging almost 10,000 ppm (dry at 3 percent O_2) for the dry wood test and 3,000 ppm for the green wood test. Per unit of fuel feed, these translate to 66 and 14 g/kg fuel, respectively. The high CO emissions were the direct consequence of the high excess air levels at which the boiler was operated: averaging almost 400 percent for the dry wood test and over 200 percent for the green wood test. NO_x emissions for both tests were below 200 ppm (dry, at 3 percent O_2), corresonding to between 1.5 and 2.0 g/kg fuel. These levels are somewhat higher than typical for wood-fired industrial boilers. Particulate emissions were approximately 3.5 g/kg fuel for both tests, in the range typical of wood-fired industrial boilers.

Paralleling the relative CO levels for the two tests, flue gas total organic emissions for the dry wood test, at between 1.4 and 3.0 g/kg fuel, were significantly higher than those for the green wood test at between 0.06 and 0.86 g/kg fuel. Emission levels for all three boiling point ranges of organics analyzed (nominally C_1 to C_6, C_7 to C_{16}, and $C_{16}+$) as well as the POM species determined, were higher in the dry wood (higher excess air) test.

For both tests the trace element composition of the mechanical collector hopper ash was similar to that of the corresponding coarse fraction (>3 μm) particulate collected. Further, the composition of the mechanical collector

hopper ash was similar for both tests, paralleling a corresponding similarity between fuel trace element composition.

Compared to coal-fired industrial boilers in the same capacity range, NO_x emissions from the wood-fired unit tested were lower. Emissions from the wood-fired boiler tested were generally less than 200 ppm (dry at 3 percent O_2), corresponding to levels in the 100 ng/J heat input range. Typical coal-fired stoker NO_x emissions are in the 300 to 400 ppm (dry at 3 percent O_2) range, corresponding to about 200 ng/J heat input. SO_2 emissions from the wood-fired boiler were also lower than for a coal-fired unit reflecting the relative fuel sulfur contents.

CO emissions from the wood-fired boiler, in several thousand ppm (at 3 percent O_2) range, were significantly higher than the typical several hundred ppm or less range from coal-fired units. However, the wood-fired unit was operated at very high excess air levels, several hundred percent excess air. Coal-fired stokers are generally operated in the 30 percent excess air range. Total semivolatile and nonvolatile (SASS train) organic emissions from the wood-fired unit in the green wood test (during which the boiler was fired at lower excess air) were comparable to corresponding emissions from a coal-fired boiler. Total organic emissions for the dry wood test (with the boiler fired at higher excess air) were higher.

Emissions of several POM species (acenaphthylene, acenaphthene, anthracene, benzofluoranthene, chrysene, fluoranthene, fluorene, naphthalene, phenanthrene, and pyrene were measured in the 0.1 to 7 µg/dscm range in one or both of the tests of this wood-fired boiler. Emissions of the same species from industrial coal-fired boilers are often in the 0.1 to 1 µg/dscm range. Thus, POM emissions from the wood-fired unit appear higher (up to an

order of magnitude higher for some species) than from corresponding coal-fired sources. Still, emission levels remain relatively low, and only of POM species not regarded as being among the most hazardous.

REFERENCES FOR SECTION 4

4-1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1982," American Conference of Governmental Industrial Hygenists, Cincinnati, Ohio, 1982.

4-2. OSHA Safety and Health Standards, 29 CFR 1910, Subpart Z.

4-3. "Water Quality Criteria Documents; Availability," Federal Register, Vol. 45, No. 231, pp. 79318 to 79379, November 28, 1980.

4-4. Brusick, D. J., and R. R. Young, "IERL-RTP Procedures Manual: Level 1 Environmental Assessment, Biological Tests," EPA-600/8-81-024, NTIS PB 82-228966, October 1981.

APPENDIX A

SAMPLING AND ANALYSIS METHODS

Emission test equipment was provided by Acurex Corporation and the Office of Research and Development of EPA. Continuous monitoring analyses for O_2, CO, and NO_x emissions were provided by personnel from the GCA Corporation contracted by EPA to operate their mobile emission monitoring laboratory. Onsite equipment provided by Acurex Corporation included a sulfur oxides analysis train (controlled condensation system equipment), the SASS train for particulate sizing and trace element and organic species collection, EPA Method 5 sampling train for total particulate emissions, and gas chromatography with flame ionization detector (GC/FID) for gaseous (C_1 to C_6) hydrocarbon analyses. Source testing by Acurex and GCA was performed simultaneously with polycyclic organic matter (POM) emissions testing by the North Carolina Department of Natural Resources and Community Development (DNR). The equipment used by the DNR consisted of an EPA Method 5 sampling train modified for the collection of semivolatile organic species as described by Battelle-Columbus Laboratories (Reference A-1). All flue gas emission sampling was performed at the stack. Wood fuel samples and flyash waste streams samples were taken by Acurex.

The following sections briefly describe the equipment and sampling procedures used by Acurex and GCA during the source evaluation of the wood-fired industrial boiler.

A.1 CONTINUOUS MONITORING SYSTEM FOR GASEOUS EMISSIONS

The continuous monitors for flue gas analysis were furnished by EPA in their mobile sampling van. The gas samples were taken from the stack downstream of the induced draft (ID) fan. One sampling probe, located at the average centroid of the stack, was used in sampling the flue gas. Flue gas O_2, CO, and NO_x were measured using the instrumentation summarized in Table A-1; calibration gases are listed in Table A-2. Figure A-1 illustrates the flue gas sampling system. The sampling probe is equipped with an in-stack filter for removal of particulate matter. The heated interface box, containing pneumatically operated valves, permitted the operator to transport calibration gas to the box and compressed air for back-flushing of sampling probe and filter. The interface box is connected to the gas conditioning system by self-regulated heat-traced teflon tubing. A two-stage condensation unit removes the water vapor from the sample prior to delivery to the distribution panel and analyses.

A.2 PARTICULATE EMISSIONS

Particulate mass tests were conducted in accordance with EPA Reference Methods 1 through 5. The Acurex High Volume Stack Sampler (HVSS) illustrated schematically in Figure A-2 was used in this program. A 1.52-m (5-ft) heated stainless-steel, glass-lined probe was used to isokinetically extract samples from the stack. Probe temperature was maintained at 120°C (250°F) as required by EPA Method 5. A glass fiber filter 142 mm (5.59 in.) in diameter heated to 120°C (250°F) was used to capture the particulates. The impinger train consisted of foam glass impingers equipped with teflon caps and 316 stainless-steel stems, collector tubes, and fittings. The first two impingers contained 100 ml of distilled water, the third was empty, and the

TABLE A-1. MOBILE LABORATORY INSTRUMENT COMPLIMENT (REFERENCE A-2)

Analyzer	Manufacturer	Model number
Oxygen (O_2)	MSA	802
Oxides of nitrogen (NO_x)	TECO	10AR
Carbon monoxide (CO)	Horiba	PIR2000

TABLE A-2. CALIBRATION GASES (REFERENCE A-2)

Standard	Diluent Gas	Standard concentration
NO	Nitrogen	148 ppm
NO	Nitrogen	202 ppm
CO	Nitrogen	258 ppm
CO	Nitrogen	1,020 ppm
O_2	Nitrogen	11.1 percent
O_2	Compressed air	20.9 percent
Zero	Nitrogen	Zero gas

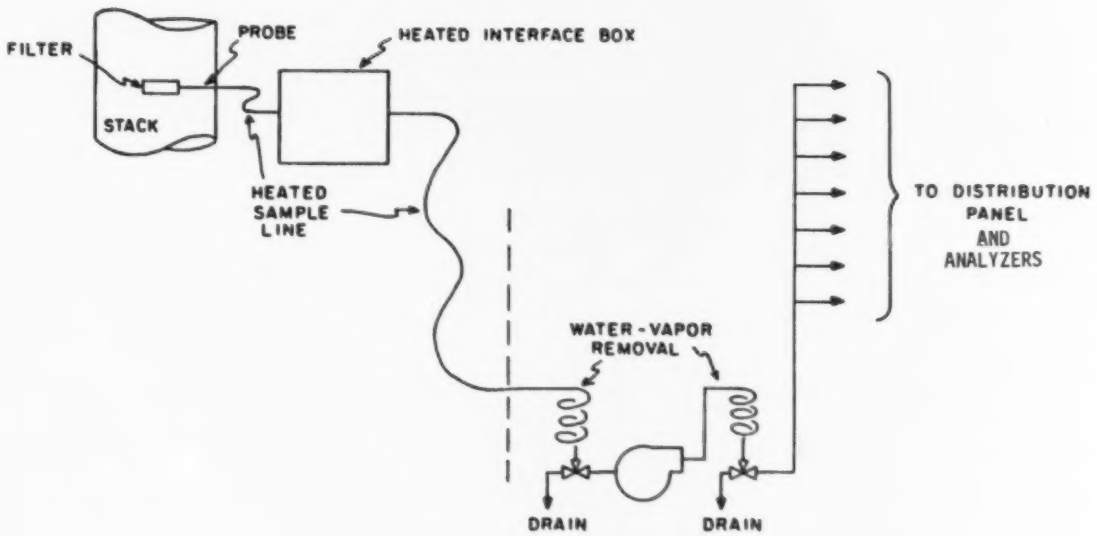
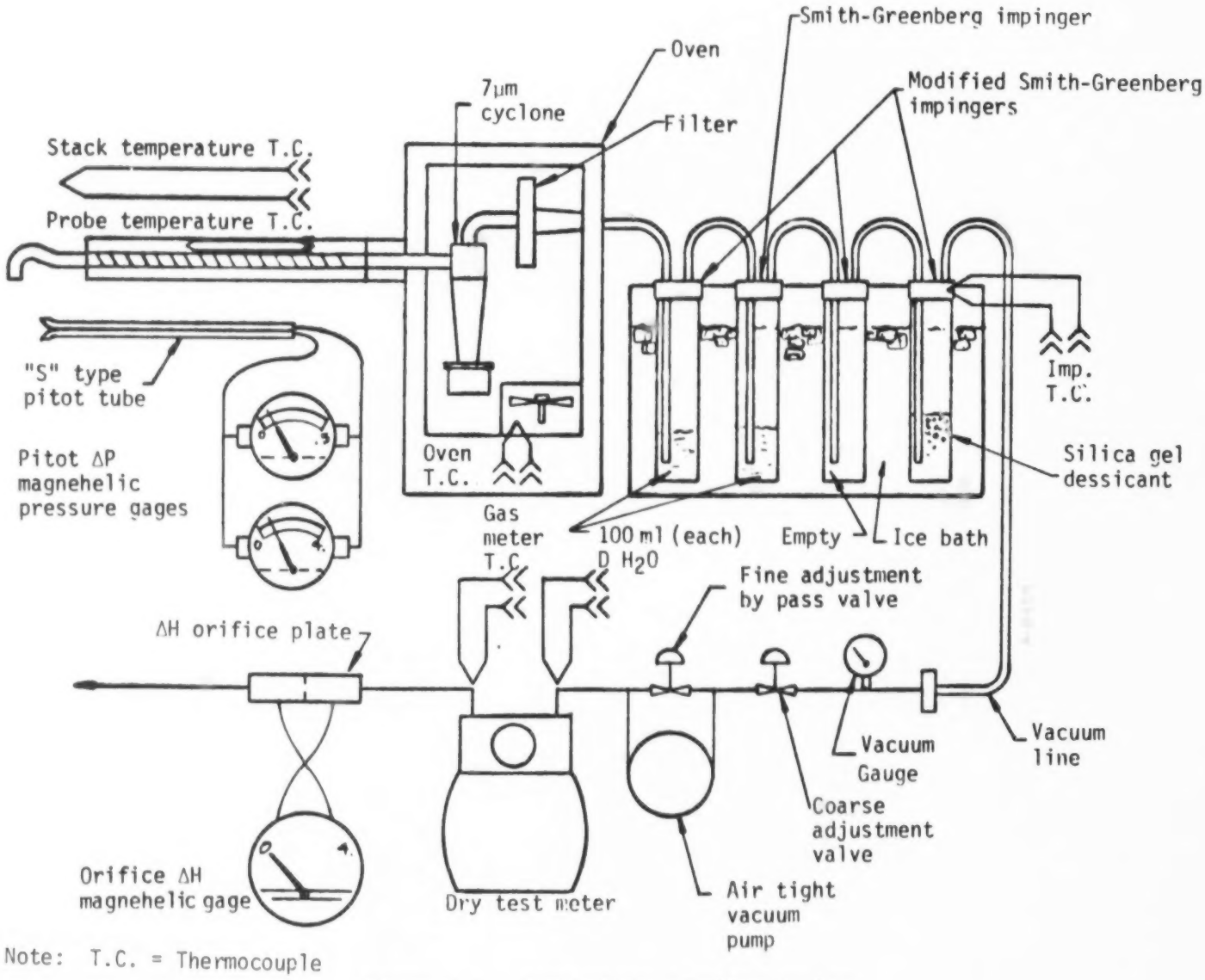


Figure A-1. Flue gas collection and conditioning system (Reference A-2).



Note: T.C. = Thermocouple

Figure A-2. Particulate sampling train.

fourth contained a known amount of silica gel. The control module is equipped with magnehelic gauges and digital thermocouple readouts, and a dry gas flowmeter for monitoring pressure and temperature in the stack and total gas sampled.

Sample collection took place on the uninsulated stack above the ID fan. The particulate tests were performed at 48 sampling points in accordance with EPA Method 1. Each test point was sampled for 2.5 min, hence a 120-min total sample time.

Figure A-3 illustrates the Method 5 sample recovery protocol utilized to measure total particulate mass collected with the HVSS train. Solid particulate matter is defined as all particulate mass collected in the front half of the train; that is the filter, the probe, and the nozzle. Condensible particulate matter is obtained from gravimetric analyses of impinger liquids and impinger rinses.

A.3 SULFUR EMISSIONS

Sulfur emissions (SO_2 and SO_3) were measured using the controlled condensation system illustrated in Figure A-4. This sampling system, designed primarily to measure vapor phase concentration of SO_3 as H_2SO_4, consists of a heated quartz probe, a Goksoyr/Ross condenser (condensation coil), impingers, a pump, and a dry gas test meter. By using the Goksoyr/Ross condenser, the gas is cooled to the dew point where SO_3 condenses as H_2SO_4. SO_2 interference is prevented by maintaining the temperature of the gas above the water dew point. Sulfur dioxide is collected in a 3 percent hydrogen peroxide solution. A more detailed discussion of the controlled condensation sampling system is given in Reference A-3.

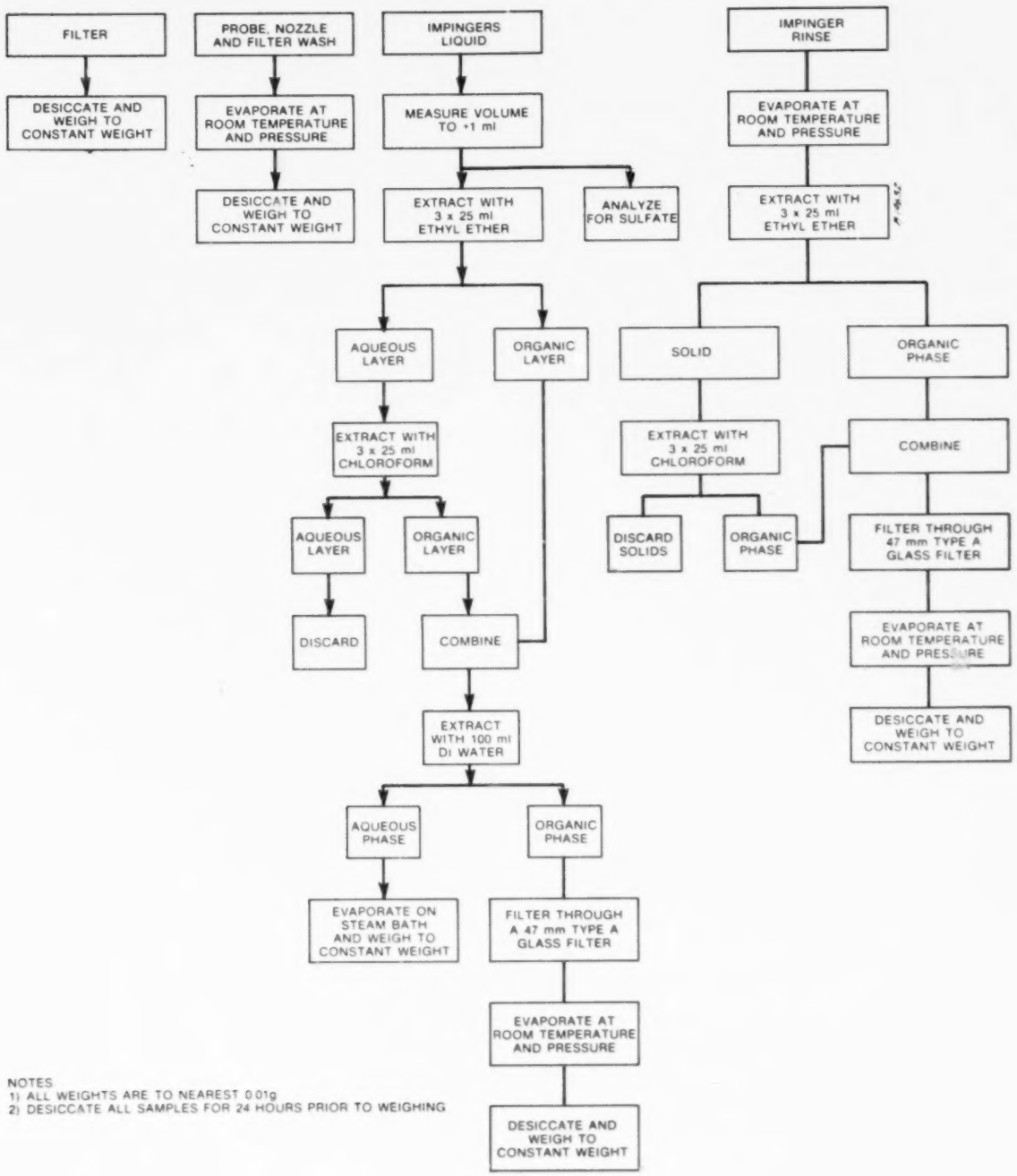
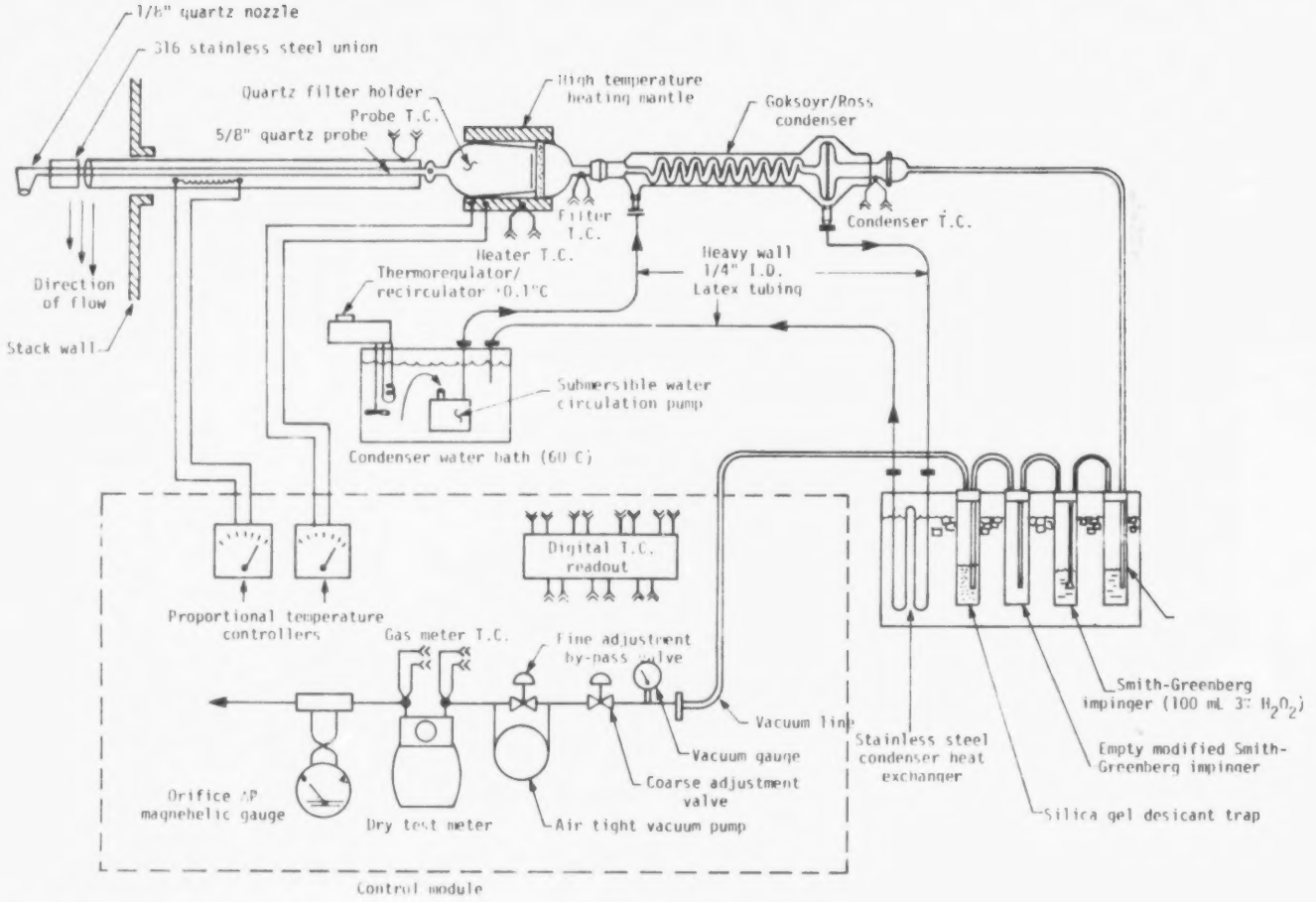

FILTER
DESICCATE AND WEIGH TO CONSTANT WEIGHT
PROBE, NOZZLE AND FILTER WASH
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
IMPINGERS LIQUID
MEASURE VOLUME TO +1 ml
EXTRACT WITH 3 x 25 ml ETHYL ETHER
ANALYZE FOR SULFATE
IMPINGER RINSE
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
EXTRACT WITH 3 x 25 ml ETHYL ETHER
AQUEOUS LAYER
ORGANIC LAYER
EXTRACT WITH 3 x 25 ml CHLOROFORM
AQUEOUS LAYER
ORGANIC LAYER
DISCARD
COMBINE
EXTRACT WITH 100 ml DI WATER
AQUEOUS PHASE
ORGANIC PHASE
EVAPORATE ON STEAM BATH AND WEIGH TO CONSTANT WEIGHT
FILTER THROUGH A 47 mm TYPE A GLASS FILTER
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
SOLID
ORGANIC PHASE
EXTRACT WITH 3 x 25 ml CHLOROFORM
DISCARD SOLIDS
ORGANIC PHASE
COMBINE
FILTER THROUGH 47 mm TYPE A GLASS FILTER
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
NOTES
1) ALL WEIGHTS ARE TO NEAREST 0.01g
2) DESICCATE ALL SAMPLES FOR 24 HOURS PRIOR TO WEIGHING

Figure A-3. Sample analysis scheme for particulate sampling train.



Note: T.C. = Thermocouple

Figure A-4. Controlled condensation system.

Both SO_2 and SO_3 (as H_2SO_4) were measured by titration with a 0.02 N NaOH using bromphenol blue and barium thorin as the indicators. Results of the titration with bromphenol blue indicator were considered questionable due to pH inbalances in the blanks and samples. Most of the samples analyzed required the addition of acid to swing the indicator color to yellow for titration to a basic end point. Although SO_2 and SO_3 analyses using this indicator showed concentrations in the range of 3 to 8 ppm, respectively, the results were considered questionable because of problems associated with pipeting errors and varying end-points.

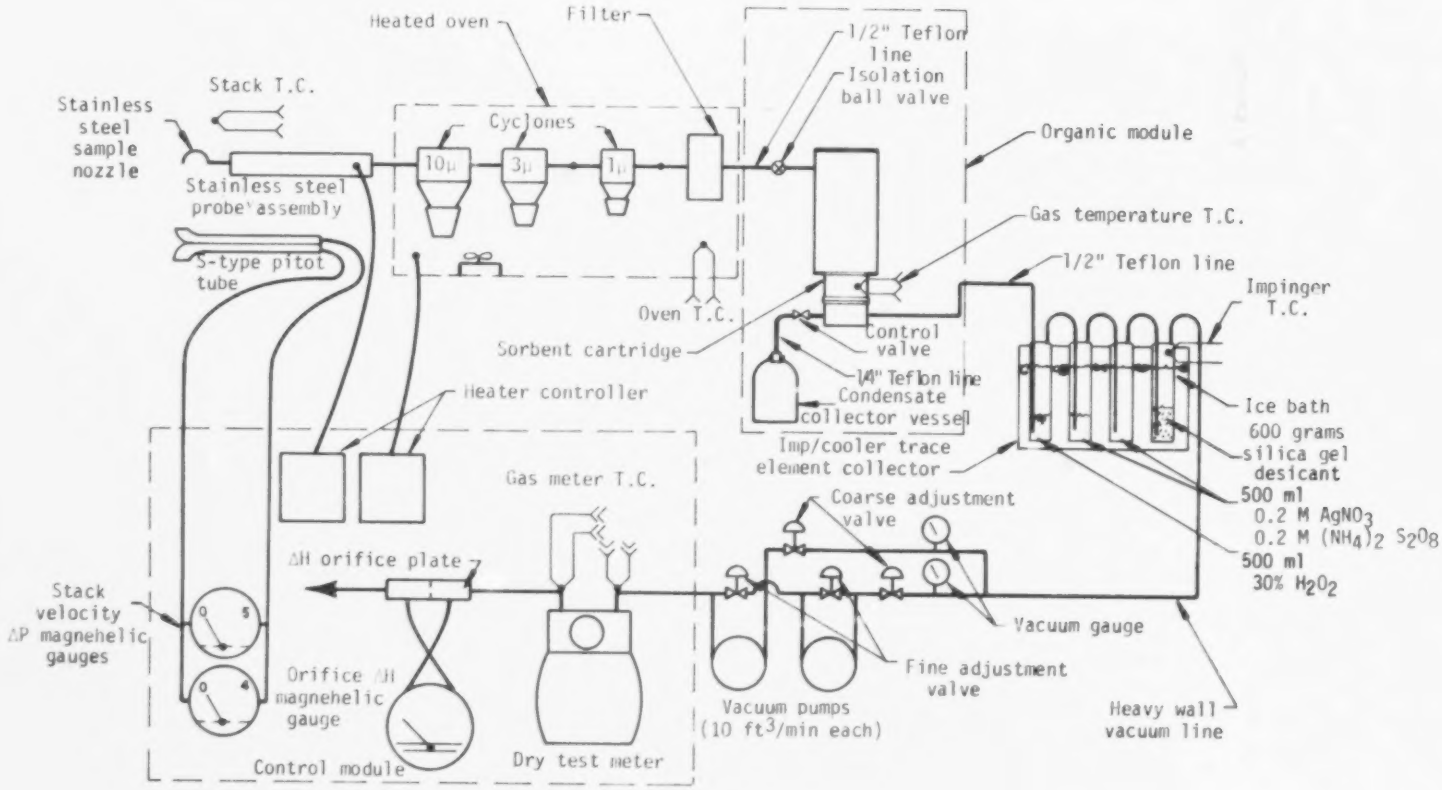
The results of the barium thorin titration seemed to be much more definitive. For the most part end-points were easily determined and the results consistent. Using this titration method, the analysis indicated that there were no detectable oxidized sulfur species in the sampled flue gas stream for either the dry or green wood tests.

A.4 TRACE ELEMENTS AND ORGANIC EMISSIONS

Emissions of inorganic trace elements and organic compounds were sampled with the source assessment sampling system (SASS). Designed for Level 1 environmental assessment (Reference A-4), the SASS collects large quantities of gas and solid samples required for subsequent analyses of inorganic and organic emissions as well as particle size measurement.

The SASS, illustrated in Figure A-5, is generally similar to the system utilized for total particulate mass emission tests (HVSS) with the exception of:

- Particulate cyclones heated in the oven with the filter to 230°C (450°F)



Note: T.C. = Thermocouple

Figure A-5. Source assessment sampling train schematic.

- The addition of a gas cooler and organic sampling module
- The addition of necessary vacuum pumps

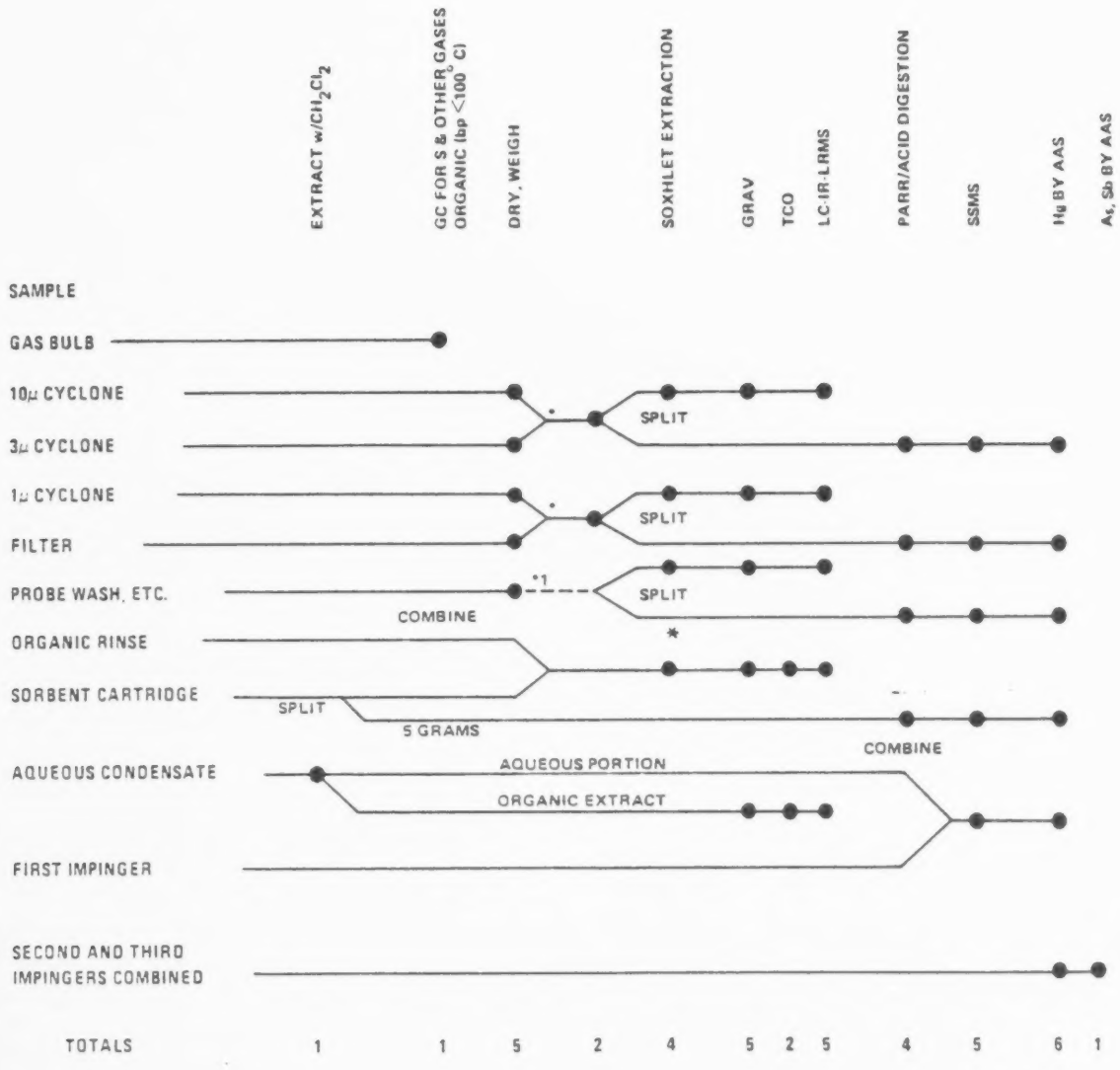
Schematics outlining the sampling and analytical procedures using the SASS equipment are presented in Figures A-6 and A-7. The following paragraphs briefly describe analytical procedures used in measuring trace elements and organic emissions.

Inorganic analyses of solid and liquid samples from the SASS train were performed by spark source mass spectroscopy (SSMS) for most of the trace elements. Atomic absorption spectrometry (AAS) was used for analyses of volatile mercury (Hg), antimony (Sb), and arsenic (As).

Quantitative information on total organic emissions was obtained by gas chromatography for total chromatographable organics (TCO) and by gravimetry (GRAV) of particulate, sorbent module (XAD-2), and condensate trap extracts. Infrared spectroscopy (IR) and gas chromatography/mass spectroscopy (GC/MS) were used for identification of organic functional groups and for determining polycyclic organic matter (POM) and other organic species concentrations in extract samples. Liquid chromatography (LC) into seven polarity fractions, followed by IR, and low resolution mass spectrometry (LRMS) of fractions containing >0.5 mg/dscm were performed to better quantify specific organic species. Figure A-8 illustrates the organic analysis methodology followed during the current program.

A.5 C_1 TO C_6 HYDROCARBON SAMPLING AND ANALYSIS

Samples of flue gas for C_1 to C_6 hydrocarbon analysis were collected using a grab sampling procedure. Flue gas was extracted from the stack at an average velocity point similar to the average velocity point selected for the SASS probe.



* If required, sample should be set aside for biological analysis at this point.

[1] This step is required to define the total mass of particulate catch. If the sample exceeds 10% of the total cyclone and filter sample weight proceed to analysis. If the sample is less than 10% of the catch, hold in reserve.

Figure A-6. Flue gas analysis protocol for SASS samples.

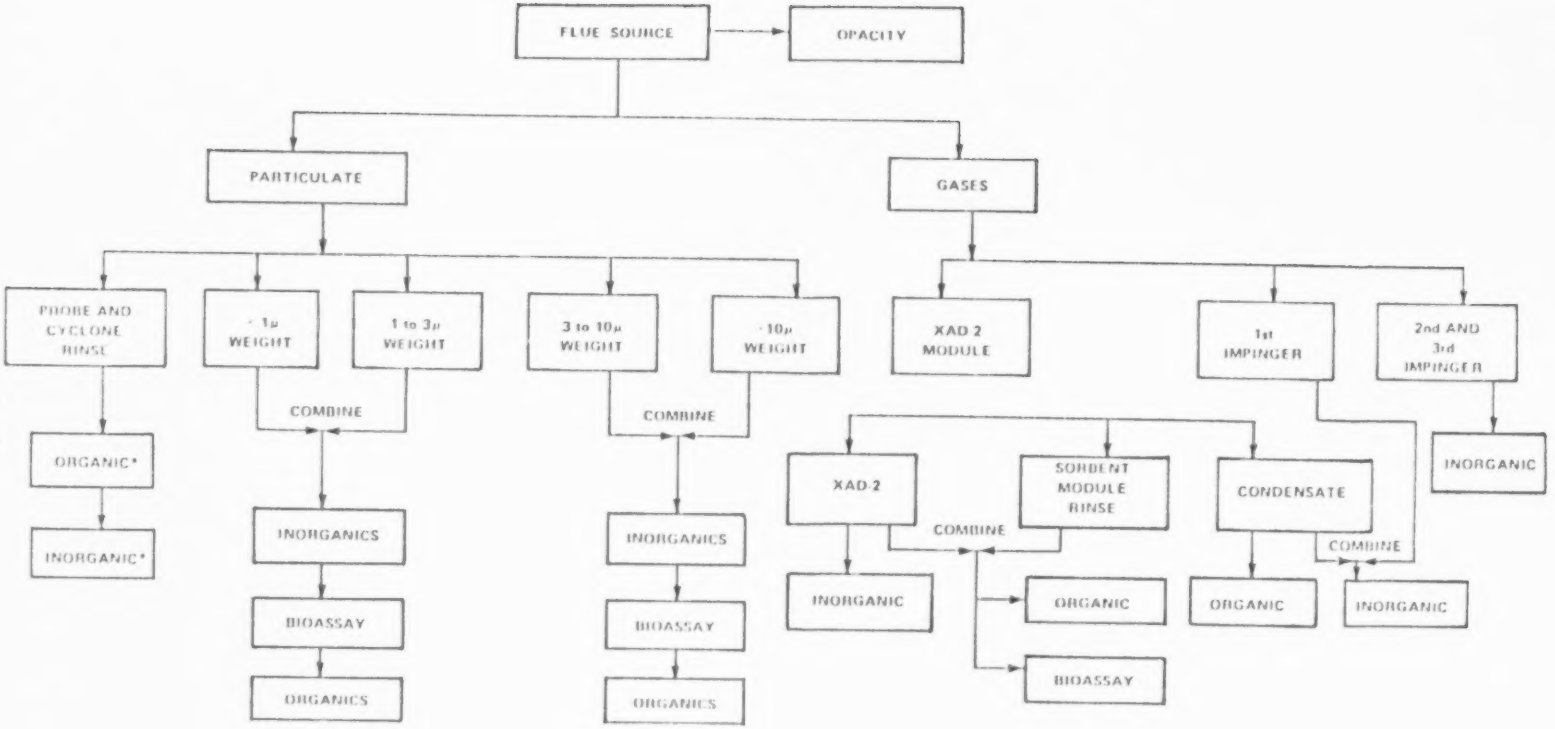


Figure A-7. Flue gas sample analysis protocol.

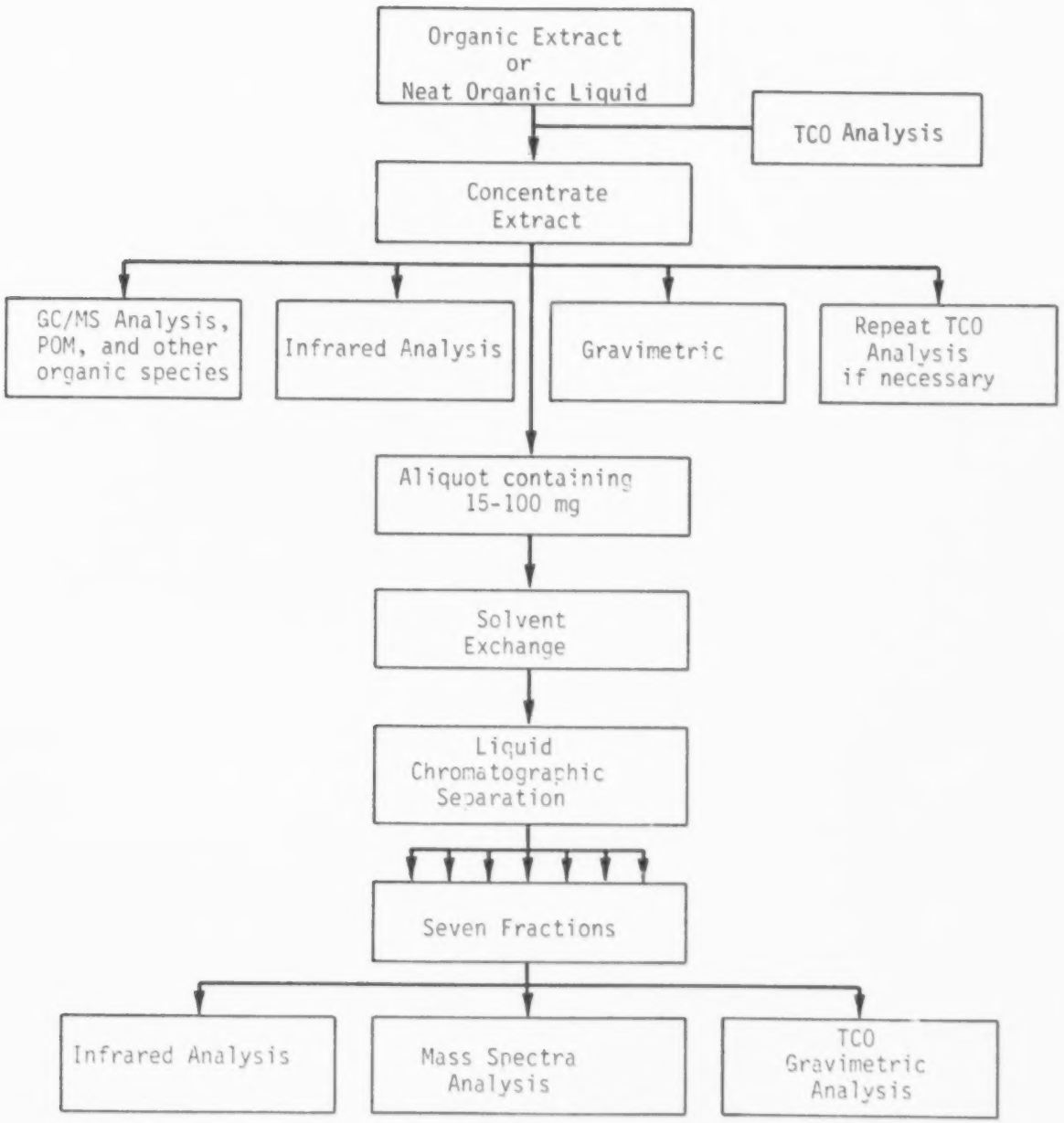


Figure A-8. Organic analysis methodology.

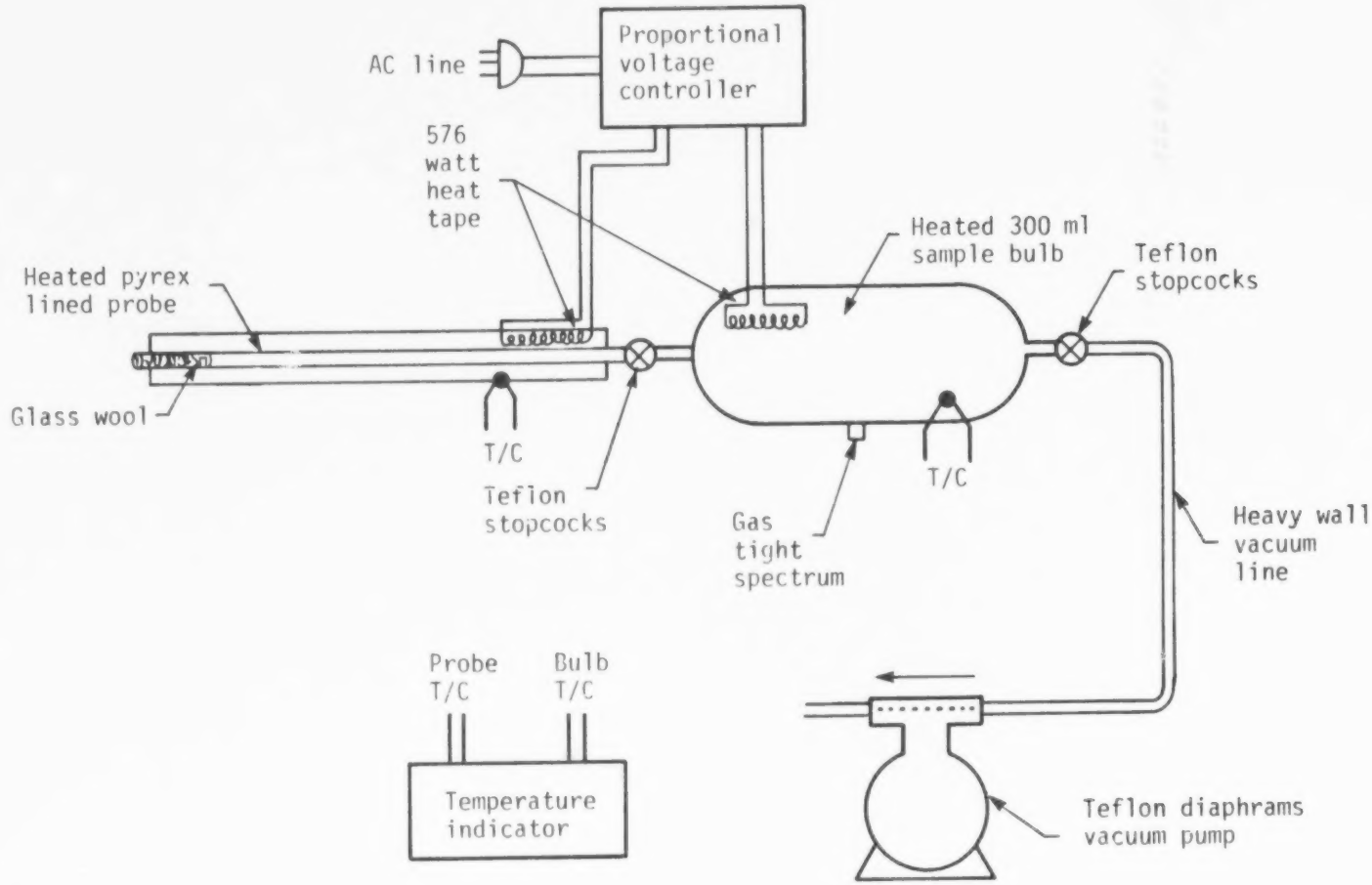


Figure A-9. Diagram of C_1 to C_6 hydrocarbon sampling system.

Samples for gaseous hydrocarbon analysis were collected using the apparatus illustrated in Figure A-9. The equipment consisted of a heated, 0.64-cm (1/4-in.) OD pyrex-lined, stainless-steel probe fitted with a glass wool filter at the probe inlet. The outlet of the probe was directly attached to a 300-ml pyrex sampling bulb. The bulb was equipped with teflon gas-tight stopcocks at each end and a septum port for sample removal. The sampling bulb was insulated with heat tape powered by a varying voltage controller. The heating jacket kept the sample gas above the dew point to minimize sample loss due to water condensation.

Prior to sampling, the gas bulb was purged with stack gas for 3-min and then sealed. The trapped flue gas was then analyzed onsite with a Carle 8500 gas chromatograph (GC) equipped with flame ionization detector. Table A-3 lists the design specifications of the Carle GC. A 1.85-m (6-ft) long 0.32-cm (1/8-in.) diameter stainless-steel column packed with Porapak Q 60/80 mesh was used to separate the hydrocarbons into their respective components (C_1 to C_6). The GC was calibrated with repeated injections of a standard gas containing C_1 to C_6 hydrocarbons (each having a concentration of 15 ppm). The chromatographic responses for the standards and the samples were recorded on a Hewlett Packard Model 3390A reporting integrator.

A.6 FUEL AND FLYASH SAMPLING

Wood fuel samples were collected at the outlet of the storage silos. Multiple samples were taken over the duration of each test. The sample used in proximate and ultimate analyses and inorganic trace element analysis represented a composite of all samples taken. Flyash collected by the mechanical collector was sampled as it entered the flyash bin. As with fuel sampling, a composite sample of the flyash was taken during each test.

TABLE A-3. GAS CHROMATOGRAPH SPECIFICATIONS

Carle Instruments, Inc., Model 8500 gas chromatograph:	
Sensitivity:	5×10^{-12} A for 1 mV output
Suppression range:	10^{-9} A
Noise:	0.5 percent peak to peak on most sensitive range
Time constant:	100 ms on all ranges except "1" range which is 200 ms
Gas required:	Carrier gas (helium) Combustion air Fuel gas (hydrogen)

REFERENCES FOR APPENDIX A

A-1. Jones, P. W., et al., "Measurement of Polycyclic Organic Material and Other Hazardous Organic Compounds in Stack Gases -- State of the Art," EPA-600/2-77-202, NTIS PB274013, October 1977.

A-2. (Deleted.)

A-3. Maddalone, R. and N. Gainer, "Process Measurement Procedures: H_2SO_4 Emissions," EPA-600/7-79-156, NTIS PB80-115959, July 1979.

A-4. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

APPENDIX B

TRACE ELEMENT CONCENTRATIONS

The following tables present sample trace element analysis results and trace element discharge stream concentrations. The tables labeled "ppm" represent element analysis results (µg/g) for each sample analyzed. Compositions for the wood fuel, mechanical collector hopper ash (flyash), its aqueous leachate, and all SASS train samples (probe wash 10 + 3 µm particulate, filter + 1 µm particulate, XAD-2 resin, first impinger, and second and third impingers) are noted.

The tables labeled "concentration" give the calculated flue gas concentration (µg/dscm) of each element corresponding to each SASS train sample, and the SASS train sum (labeled "stack exhaust").

Symbols appearing in the tables are:

DSCM	Dry standard cubic meter at 1 atm and 20°C
MCG	Microgram
PPM	Part per million by weight
<	Less than
>	Greater than
N	Element not analyzed

Trace elements having concentrations less than the detectable limit or having a blank value greater than the sample value were given an arbitrary concentration of zero.

Detectability limits for the various SASS, liquid, and solid stream samples were the following:

- 10 + 3 μm cyclones -- <0.1 μg/g
- Filter -- <0.1 μg/g
- XAD-2 -- <0.1 μg/g
- Impinger and organic module concentrate -- <0.1 μg/ml
- Wood sample -- <0.1 μg/g
- Mechanical hopper ash -- <01. μg/g

The data inputs to the computer code for calculation of trace element flowrates were the following:

Test 1 (dry wood)

- Wood flowrate = 0.29 kg/s
- Heating value of wood = 17,915 KJ/kg
- Gas volume sampled by SASS = 21.623 dscm
- Calculated flue gas flowrate = 6.36 dscm/s
- SASS 10 + 3 μm cyclone catch = 1.8191g
- SASS 1 μm cyclone + filter catch = 1.6036g
- XAD-2 weight = 130g
- SASS impinger 1 final volume = 630 ml
- SASS impingers 2 + 3 final volume = 1,390 ml

Test 2 (green wood)

- Wood flowrate = 0.54 kg/s
- Heating value of wood = 13,318 KJ/kg
- Gas volume sampled by SASS = 27.065 dscm

- Calculated flue gas flowrate = 5.97 dscm/s
- SASS 10 + 3 μm cyclone catch = 7.1458g
- SASS 1 μm cyclone + filter catch = 2.1976g
- XAD-2 weight = 130g
- SASS impinger 1 final volume = 1,325 ml
- SASS impingers 2 + 3 final volume = 1,340 ml

ETHAN ALLEN
TEST 1 - DRY WOOD
PPM

ELEMENT	10U + 3U CYCLONES	1U + FILTER	XAD-2	FIRST IMPINGER	2ND & 3RD IMPINGERS
URANIUM	.100E+01	<.985E-01	.0 E+00	.0 E+00	N.0 E+00
THORIUM	.400E+01	.197E+00	.0 E+00	.0 E+00	.0 E+00
BISMUTH	.0 E+00	<.985E-01	.0 E+00	.0 E+00	.0 E+00
LEAD	.410E+02	.158E+02	.100E+00	.0 E+00	N.0 E+00
THALLIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	.0 E+00
MERCURY	<.830E+00	<.985E+00	.100E+00	.170E-01	<.930E-03
PLATINUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
TUNGSTEN	.500E+01	.591E+00	.0 E+00	.0 E+00	N.0 E+00
TANTALUM	.0 E+00	.197E+00	.0 E+00	.0 E+00	N.0 E+00
HAFNIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
LUTETIUM	.100E+00	<.985E-01	.0 E+00	.0 E+00	N.0 E+00
YTTERBIUM	.900E+00	.985E-01	.0 E+00	.0 E+00	N.0 E+00
THULIUM	.100E+00	<.985E-01	.0 E+00	.0 E+00	N.0 E+00
ERBIUM	.400E+00	<.985E-01	.0 E+00	.0 E+00	N.0 E+00
HOLMIUM	.500E+00	.985E-01	.0 E+00	.0 E+00	N.0 E+00
DYSPROSIUM	.200E+01	.197E+00	.0 E+00	.0 E+00	N.0 E+00
TERBIUM	.100E+01	.985E-01	.0 E+00	.0 E+00	N.0 E+00
GADOLINIUM	.100E+01	.296E+00	.0 E+00	.0 E+00	N.0 E+00
EUROPIUM	.500E+00	.985E-01	.0 E+00	N.0 E+00	.0 E+00
SAMARIUM	.500E+01	.887E+00	.0 E+00	.0 E+00	N.0 E+00
NEODYMIUM	.400E+01	.887E+00	.0 E+00	.0 E+00	N.0 E+00
PRASEODYMIUM	.200E+01	.887E+00	.0 E+00	.0 E+00	N.0 E+00
CERIUM	.130E+02	.522E+01	.0 E+00	.0 E+00	N.0 E+00
LANTHANUM	.420E+02	.906E+01	<.200E+01	.0 E+00	N.0 E+00
BARIUM	>.100E+04	>.975E+03	.0 E+00	.420E-01	N.0 E+00
CESIUM	.600E+00	.197E+00	.200E+00	.0 E+00	N.0 E+00
IODINE	.100E+01	.985E-01	.100E+00	.0 E+00	N.0 E+00
TELLURIUM	.300E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
ANTIMONY	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	<.930E-02
TIN	.400E+00	.985E-01	.0 E+00	.0 E+00	N.0 E+00
CADMIUM	.700E+00	.197E+00	.0 E+00	.0 E+00	N.0 E+00
SILVER	.400E+01	.394E+01	.130E+03	.200E+00	N.0 E+00
MOLYBDENUM	.100E+02	.394E+00	.0 E+00	.192E+00	N.0 E+00
NIOBIUM	.500E+01	.0 E+00	.0 E+00	.500E-02	N.0 E+00
ZIRCONIUM	.600E+01	.0 E+00	.180E+01	.290E-01	N.0 E+00
YTTRIUM	.700E+01	.266E+01	.0 E+00	.0 E+00	N.0 E+00
STRONTIUM	>.100E+04	.195E+03	.0 E+00	.300E-02	N.0 E+00
RUBIDIUM	.790E+02	.590E+02	.0 E+00	.800E-01	N.0 E+00
BROMINE	.800E+01	.0 E+00	.170E+01	.300E-01	N.0 E+00
SELENIUM	.500E+00	.296E+01	.0 E+00	.0 E+00	N.0 E+00
ARSENIC	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	<.930E-02
GERMANIUM	.500E+00	.197E+00	.0 E+00	.0 E+00	N.0 E+00
GALLIUM	.700E+01	.690E+00	.0 E+00	<.100E-02	N.0 E+00
ZINC	>.100E+04	.386E+03	.200E+01	.980E+00	N.0 E+00
COPPER	.980E+02	.287E+02	.0 E+00	.500E-02	N.0 E+00

ETHAN ALLEN
TEST 1 - DRY WOOD
PPM

PPM

ELEMENT	10U + 3U CYCLONES	1U + FILTER	XAD-2	FIRST IMPINGER	2ND & 3RD IMPINGERS
NICKEL	.170E+02	.345E+01	.190E+02	.300E-01	N.0 E+00
COBALT	.200E+01	.985E-01	.900E+00	.0 E+00	N.0 E+00
IRON	>.100E+04	>.956E+03	.600E+01	.900E-01	N.0 E+00
MANGANESE	>.100E+04	>.985E+03	.0 E+00	.400E-02	N.0 E+00
CHROMIUM	.260E+02	.404E+01	.0 E+00	.196E+00	N.0 E+00
VANADIUM	.170E+02	.197E+00	.0 E+00	.400E-02	N.0 E+00
TITANIUM	>.100E+04	.0 E+00	.0 E+00	.600E-01	N.0 E+00
SCANDIUM	.500E+00	.0 E+00	<.100E+00	<.100E-02	N.0 E+00
CALCIUM	>.100E+04	U.0 E+00	.0 E+00	.0 E+00	N.0 E+00
POTASSIUM	>.100E+04	>.979E+03	.220E+02	.500E+00	N.0 E+00
CHLORINE	.680E+03	.916E+02	.270E+02	.360E+00	N.0 E+00
SULFUR	>.100E+04	>.982E+03	.154E+03	>.990E+01	N.0 E+00
PHOSPHORUS	>.100E+04	>.975E+03	.0 E+00	.0 E+00	N.0 E+00
SILICON	>.100E+04	U.0 E+00	.0 E+00	>.940E+01	N.0 E+00
ALUMINUM	>.100E+04	U.0 E+00	.100E+01	.400E-01	N.0 E+00
MAGNESIUM	>.100E+04	U.0 E+00	.600E+01	.670E+00	N.0 E+00
SODIUM	>.100E+04	U.0 E+00	.600E+02	>.940E+01	N.0 E+00
FLUORINE	>.100E+04	.0 E+00	.0 E+00	.230E+01	N.0 E+00
BORON	.190E+03	.0 E+00	.0 E+00	.900E-02	N.0 E+00
BERYLLIUM	<.100E+00	<.985E-01	.0 E+00	.0 E+00	N.0 E+00
LITHIUM	.300E+01	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
FLUORIDE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
CHLORIDE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
BROMIDE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
NITRATE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
NITRITE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
SULFITE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
SULFATE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
PHOSPHATE	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00
AMMONIA	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00

ETHAN ALLEN
TEST 1 - DRY WOOD
PPM

PPM

ELEMENT	FUEL: DRY WOOD	FLYASH	FLYASH LEACHATE
URANIUM	<.300E-01	.100E+01	.0 E+00
THORIUM	<.400E-01	.700E+01	.0 E+00
BISMUTH	.0 E+00	.0 E+00	.0 E+00
LEAD	.400E+00	.280E+02	.800E-01
THALLIUM	.300E-01	.0 E+00	.0 E+00
MERCURY	<.500E-01	<.500E-01	.0 E+00
PLATINUM	.0 E+00	.0 E+00	<.500E-02
TUNGSTEN	.0 E+00	.900E+00	.900E-01
TANTALUM	.0 E+00	.0 E+00	.900E-02
HAFNIUM	.0 E+00	.900E+00	.0 E+00
LUTETIUM	.0 E+00	.0 E+00	.0 E+00
YTTERBIUM	.0 E+00	.0 E+00	.0 E+00
THULIUM	.0 E+00	.0 E+00	.0 E+00
ERBIUM	.0 E+00	.0 E+00	.600E+00
HOLMIUM	.0 E+00	.0 E+00	.800E+00
DYSPROSIUM	.0 E+00	.0 E+00	.0 E+00
TERBIUM	.0 E+00	.900E+00	.0 E+00
GADOLINIUM	.0 E+00	.200E+01	.0 E+00
EUROPIUM	.0 E+00	.400E+00	.0 E+00
SAMARIUM	<.200E-01	.300E+01	.0 E+00
NEODYMIUM	<.100E-01	.400E+01	.0 E+00
PRASEODYMIUM	.200E-01	.400E+01	.0 E+00
CERIUM	.100E+00	.200E+02	.200E-02
LANTHANUM	.200E+00	.160E+02	.300E-02
BARIUM	.210E+02	>.100E+04	>.100E+02
CESIUM	.600E-01	.600E+00	.0 E+00
IODINE	.900E-01	.700E+00	.500E-01
TELLURIUM	.300E-01	.500E+00	<.800E-02
ANTIMONY	N.0 E+00	N.0 E+00	N.0 E+00
TIN	<.100E-01	.500E+00	<.900E-02
CADMIUM	.300E-01	.100E+01	.200E-02
SILVER	.200E+00	.0 E+00	.0 E+00
MOLYBDENUM	<.100E-01	.200E+01	.300E-02
NIOBIUM	<.100E-01	.400E+01	.0 E+00
ZIRCONIUM	.700E-01	.100E+02	.200E-02
YTTRIUM	.400E-01	.110E+02	<.100E-02
STRONTIUM	.700E+01	.620E+03	>.100E+02
RUBIDIUM	.400E+00	.130E+03	>.100E+02
BROMINE	.400E+00	.600E+01	.400E+00
SELENIUM	.100E-01	.500E+01	.0 E+00
ARSENIC	N.0 E+00	N.0 E+00	N.0 E+00
GERMANIUM	.0 E+00	.300E+00	<.100E-02
GALLIUM	.100E-01	.500E+01	.300E-02
ZINC	.290E+02	.410E+03	.200E-01
COPPER	.600E+01	.520E+02	.300E-01

ETHAN ALLEN
TEST 1 - DRY WOOD
PPM

PPM

ELEMENT	FUEL: DRY WOOD	FLYASH	FLYASH LEACHATE
NICKEL	.800E-01	.600E+01	.200E-01
COBALT	.100E+00	.300E+01	<.200E-02
IRON	.110E+02	>.100E+04	.600E+01
MANGANESE	>.450E+02	>.100E+04	.500E-02
CHROMIUM	.100E+00	.400E+01	.100E+00
VANADIUM	.800E-01	.290E+02	.800E-01
TITANIUM	.500E-01	>.100E+04	.200E+01
SCANDIUM	.0 E+00	.900E+00	<.100E-02
CALCIUM	>.100E+03	>.100E+04	>.100E+02
POTASSIUM	>.540E+02	>.100E+04	>.100E+02
CHLORINE	.100E+02	.870E+03	>.100E+02
SULFUR	>.270E+02	>.100E+04	>.100E+02
PHOSPHORUS	.190E+02	>.100E+04	.200E+00
SILICON	>.100E+03	>.100E+04	>.100E+02
ALUMINUM	>.400E+01	>.100E+04	.100E+00
MAGNESIUM	>.100E+03	>.100E+04	.500E-01
SODIUM	>.110E+02	>.100E+04	>.100E+02
FLUORINE	.600E+00	.240E+02	.400E+01
BORON	.400E-01	.140E+03	.100E-01
BERYLLIUM	.0 E+00	.300E+00	.0 E+00
LITHIUM	.300E-01	.500E+01	.100E-01
FLUORIDE	N.0 E+00	.800E+00	N.0 E+00
CHLORIDE	N.0 E+00	.560E+03	N.0 E+00
BROMIDE	N.0 E+00	.400E+02	N.0 E+00
NITRATE	N.0 E+00	.100E+03	N.0 E+00
NITRITE	N.0 E+00	.240E+03	N.0 E+00
SULFITE	N.0 E+00	<.800E+01	N.0 E+00
SULFATE	N.0 E+00	.800E+03	N.0 E+00
PHOSPHATE	N.0 E+00	.200E+00	N.0 E+00
AMMONIA	N.0 E+00	.500E+01	N.0 E+00

ETHAN ALLEN
TEST 1 - DRY WOOD

CONCENTRATION
MCG/DSCM

ELEMENT	1OU + 3U CYCLONES	1U + FILTER	XAD-2	FIRST IMPINGER	2ND & 3RD IMPINGERS
URANIUM	.841E-01	< .731E-02	.0 E+00	.0 E+00	N .0 E+00
THORIUM	.337E+00	.146E-01	.0 E+00	.0 E+00	.0 E+00
BISMUTH	.0 E+00	< .731E-02	.0 E+00	.0 E+00	.0 E+00
LEAD	.345E+01	.117E+01	.601E+00	.0 E+00	N .0 E+00
THALLIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	.0 E+00
MERCURY	< .698E-01	< .731E-01	.601E+00	.495E+00	< .598E-01
PLATINUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
TUNGSTEN	.421E+00	.438E-01	.0 E+00	.0 E+00	N .0 E+00
TANTALUM	.0 E+00	.146E-01	.0 E+00	.0 E+00	N .0 E+00
HAFNIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
LUTETIUM	.841E-02	< .731E-02	.0 E+00	.0 E+00	N .0 E+00
YTTERBIUM	.757E-01	.731E-02	.0 E+00	.0 E+00	N .0 E+00
THULIUM	.841E-02	< .731E-02	.0 E+00	.0 E+00	N .0 E+00
ERBIUM	.337E-01	< .731E-02	.0 E+00	.0 E+00	N .0 E+00
HOLMIUM	.421E-01	.731E-02	.0 E+00	.0 E+00	N .0 E+00
DYSPROSIUM	.168E+00	.146E-01	.0 E+00	.0 E+00	N .0 E+00
TERBIUM	.841E-01	.731E-02	.0 E+00	.0 E+00	N .0 E+00
GADOLINIUM	.841E-01	.219E-01	.0 E+00	.0 E+00	N .0 E+00
EUROPIUM	.421E-01	.731E-02	.0 E+00	N .0 E+00	.0 E+00
SAMARIUM	.421E+00	.658E-01	.0 E+00	.0 E+00	N .0 E+00
NEODYMIUM	.337E+00	.658E-01	.0 E+00	.0 E+00	N .0 E+00
PRASEODYMIUM	.168E+00	.658E-01	.0 E+00	.0 E+00	N .0 E+00
CERIUM	.109E+01	.387E+00	.0 E+00	.0 E+00	N .0 E+00
LANTHANUM	.353E+01	.672E+00	< .120E+02	.0 E+00	N .0 E+00
BARIUM	> .841E+02	> .723E+02	.0 E+00	.122E+01	N .0 E+00
CESIUM	.505E-01	.146E-01	.120E+01	.0 E+00	N .0 E+00
IODINE	.841E-01	.731E-02	.601E+00	.0 E+00	N .0 E+00
TELLURIUM	.252E-01	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
ANTIMONY	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	< .598E+00
TIN	.337E-01	.731E-02	.0 E+00	.0 E+00	N .0 E+00
CADMIUM	.589E-01	.146E-01	.0 E+00	.0 E+00	N .0 E+00
SILVER	.337E+00	.292E+00	.781E+03	.583E+01	N .0 E+00
MOLYBDENUM	.841E+00	.292E-01	.0 E+00	.559E+01	N .0 E+00
NIOBIUM	.421E+00	.0 E+00	.0 E+00	.146E+00	N .0 E+00
ZIRCONIUM	.505E+00	.0 E+00	.108E+02	.845E+00	N .0 E+00
YTTRIUM	.589E+00	.197E+00	.0 E+00	.0 E+00	N .0 E+00
STRONTIUM	> .841E+02	.145E+02	.0 E+00	.874E-01	N .0 E+00
RUBIDIUM	.665E+01	.438E+01	.0 E+00	.233E+01	N .0 E+00
BROMINE	.673E+00	.0 E+00	.102E+02	.874E+00	N .0 E+00
SELENIUM	.421E-01	.219E+00	.0 E+00	.0 E+00	N .0 E+00
ARSENIC	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	< .598E+00
GERMANIUM	.421E-01	.146E-01	.0 E+00	.0 E+00	N .0 E+00
GALLIUM	.589E+00	.512E-01	.0 E+00	< .291E-01	N .0 E+00
ZINC	> .841E+02	.286E+02	.120E+02	.286E+02	N .0 E+00
COPPER	.824E+01	.213E+01	.0 E+00	.146E+00	N .0 E+00

ETHAN ALLEN
TEST 1 - DRY WOOD

CONCENTRATION MCG/DSCM

ELEMENT	4OU + 3U CYCLONES	1U + FILTER	XAD-2	FIRST IMPINGER	2ND & 3RD IMPINGERS
NICKEL	.143E+01	.256E+00	.114E+03	.874E+00	N .0 E+00
COBALT	.168E+00	.731E-02	.541E+01	.0 E+00	N .0 E+00
IRON	> .841E+02	> .709E+02	.361E+02	.262E+01	N .0 E+00
MANGANESE	> .841E+02	> .730E+02	.0 E+00	.117E+00	N .0 E+00
CHROMIUM	.219E+01	.300E+00	.0 E+00	.571E+01	N .0 E+00
VANADIUM	.143E+01	.146E-01	.0 E+00	.117E+00	N .0 E+00
TITANIUM	> .841E+02	.0 E+00	.0 E+00	.175E+01	N .0 E+00
SCANDIUM	.421E-01	.0 E+00	< .601E+00	< .291E-01	N .0 E+00
CALCIUM	> .841E+02	U .0 E+00	.0 E+00	.0 E+00	N .0 E+00
POTASSIUM	> .841E+02	> .726E+02	.132E+03	.146E+02	N .0 E+00
CHLORINE	.572E+02	.680E+01	.162E+03	.105E+02	N .0 E+00
SULFUR	> .841E+02	> .729E+02	.926E+03	> .288E+03	N .0 E+00
PHOSPHORUS	> .841E+02	> .723E+02	.0 E+00	.0 E+00	N .0 E+00
SILICON	> .841E+02	U .0 E+00	.0 E+00	> .274E+03	N .0 E+00
ALUMINUM	> .841E+02	U .0 E+00	.601E+01	.117E+01	N .0 E+00
MAGNESIUM	> .841E+02	U .0 E+00	.361E+02	.195E+02	N .0 E+00
SODIUM	> .841E+02	U .0 E+00	.361E+03	> .274E+03	N .0 E+00
FLUORINE	> .841E+02	.0 E+00	.0 E+00	.670E+02	N .0 E+00
BORON	.160E+02	.0 E+00	.0 E+00	.262E+00	N .0 E+00
BERYLLIUM	< .841E-02	< .731E-02	.0 E+00	.0 E+00	N .0 E+00
LITHIUM	.252E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
FLUORIDE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
CHLORIDE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
BROMIDE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
NITRATE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
NITRITE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
SULFITE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
SULFATE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
PHOSPHATE	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00
AMMONIA	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00

CONCENTRATION	ETHAN ALLEN TEST 1 - DRY WOOD MCG/DSCM
ELEMENT	STACK EXHAUST
URANIUM	.841E-01<X<.914E-01
THORIUM	.351E+00
BISMUTH	< .731E-02
LEAD	.522E+01
THALLIUM	.0 E+00
MERCURY	.110E+01<X<.130E+01
PLATINUM	.0 E+00
TUNGSTEN	.465E+00
TANTALUM	.146E-01
HAFNIUM	.0 E+00
LUTETIUM	.841E-02<X<.157E-01
YTTERBIUM	.830E-01
THULIUM	.841E-02<X<.157E-01
ERBIUM	.337E-01<X<.410E-01
HOLMIUM	.494E-01
DYSPROSIUM	.183E+00
TERBIUM	.914E-01
GADOLINIUM	.106E+00
EUROPIUM	.494E-01
SAMARIUM	.486E+00
NEODYMIUM	.402E+00
PRASEODYMIUM	.234E+00
CERIUM	.148E+01
LANTHANUM	.421E+01<X<.162E+02
BARIUM	> .158E+03
CESIUM	.127E+01
IODINE	.693E+00
TELLURIUM	.252E-01
ANTIMONY	< .598E+00
TIN	.410E-01
CADMIUM	.735E-01
SILVER	.787E+03
MOLYBDENUM	.646E+01
NIOBIUM	.566E+00
ZIRCONIUM	.122E+02
YTTRIUM	.786E+00
STRONTIUM	> .987E+02
RUBIDIUM	.134E+02
BROMINE	.118E+02
SELENIUM	.261E+00
ARSENIC	< .598E+00
GERMANIUM	.567E-01
GALLIUM	.640E+00<X<.669E+00
ZINC	> .153E+03
COPPER	.105E+02

CONCENTRATION	ETHAN ALLEN TEST 1 - DRY WOOD MCG/DSCM
ELEMENT	STACK EXHAUST
NICKEL	.117E+03
COBALT	.559E+01
IRON	> .194E+03
MANGANESE	> .157E+03
CHROMIUM	.820E+01
VANADIUM	.156E+01
TITANIUM	> .859E+02
SCANDIUM	.421E-01<X<.672E+00
CALCIUM	> .841E+02
POTASSIUM	> .304E+03
CHLORINE	.237E+03
SULFUR	> .137E+04
PHOSPHORUS	> .156E+03
SILICON	> .358E+03
ALUMINUM	> .913E+02
MAGNESIUM	> .140E+03
SODIUM	> .719E+03
FLUORINE	> .151E+03
BORON	.162E+02
BERYLLIUM	< .157E-01
LITHIUM	.252E+00
FLUORIDE	.0 E+00
CHLORIDE	.0 E+00
BROMIDE	.0 E+00
NITRATE	.0 E+00
NITRITE	.0 E+00
SULFITE	.0 E+00
SULFATE	.0 E+00
PHOSPHATE	.0 E+00
AMMONIA	.0 E+00

ETHAN ALLEN
TEST 2 - WET WOOD
PPM

PPM

ELEMENT	10U + 3U CYCLONES	1U + FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
URANIUM	.200E+01	.144E+00	.0 E+00	.0 E+00	N.0 E+00
THORIUM	.300E+01	.144E+00	.0 E+00	.0 E+00	N.0 E+00
BISMUTH	.300E+00	.288E+00	.0 E+00	.0 E+00	N.0 E+00
LEAD	.630E+02	.115E+02	.0 E+00	.700E-02	N.0 E+00
THALLIUM	.0 E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
MERCURY	<.114E+01	<.719E+00	<.420E-01	<.140E-02	<.100E-02
PLATINUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
TUNGSTEN	.0 E+00	.359E+00	.0 E+00	.0 E+00	N.0 E+00
TANTALUM	.0 E+00	<.719E-01	.0 E+00	.0 E+00	.0 E+00
HAFNIUM	.200E+01	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
LUTETIUM	.200E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
YTTERBIUM	.200E+01	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
THULIUM	.200E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
ERBIUM	.600E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
HOLMIUM	.800E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
DYSPROSIUM	.300E+01	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
TERBIUM	.700E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
GADOLINIUM	.200E+01	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
EUROPIUM	.700E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
SAMARIUM	.300E+01	.288E+00	.0 E+00	.0 E+00	N.0 E+00
NEODYMIUM	.400E+01	.288E+00	.0 E+00	.900E-02	N.0 E+00
PRASEODYMIUM	.800E+01	.719E-01	.0 E+00	.200E-02	N.0 E+00
CERIUM	.410E+02	.216E+00	.0 E+00	.500E-02	N.0 E+00
LANTHANUM	.720E+02	.863E+00	.0 E+00	.600E-02	N.0 E+00
BARIUM	>.100E+04	>.712E+03	.300E+00	.192E+00	N.0 E+00
CESIUM	.100E+01	<.719E-01	.0 E+00	<.100E-02	N.0 E+00
IODINE	.100E+01	.719E-01	.0 E+00	.0 E+00	N.0 E+00
TELLURIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
ANTIMONY	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	<.100E-01
TIN	.100E+01	.216E+00	.0 E+00	.500E-01	N.0 E+00
CADMIUM	.300E+01	.144E+00	.0 E+00	.100E-02	N.0 E+00
SILVER	<.100E+01	.144E+01	.190E+01	.100E+00	N.0 E+00
MOLYBDENUM	.400E+01	.288E+00	.600E+00	.100E-02	N.0 E+00
NIOBIUM	.600E+01	.0 E+00	.0 E+00	.900E-02	N.0 E+00
ZIRCONIUM	.220E+02	.719E+00	.300E+00	.900E-02	N.0 E+00
YTTRIUM	.130E+02	.719E-01	.0 E+00	.100E-02	N.0 E+00
STRONTIUM	>.100E+04	.561E+02	.100E+00	.290E-01	N.0 E+00
RUBIDIUM	.300E+03	.215E+02	.0 E+00	.200E-01	N.0 E+00
BROMINE	.140E+02	.0 E+00	.170E+01	.0 E+00	N.0 E+00
SELENIUM	.200E+01	.719E+00	.0 E+00	.100E-01	N.0 E+00
ARSENIC	N.0 E+00	N.0 E+00	N.0 E+00	N.0 E+00	<.100E-01
GERMANIUM	.400E+00	.719E-01	.0 E+00	.0 E+00	N.0 E+00
GALLIUM	.500E+01	.503E+00	.0 E+00	.600E-02	N.0 E+00
ZINC	.460E+03	.426E+03	.220E+02	.180E+00	N.0 E+00
COPPER	.840E+02	.137E+02	.700E+01	.450E-01	N.0 E+00

ETHAN ALLEN
TEST 2 - WET WOOD

PPM

ELEMENT	10U + 3U CYCLONES	1U + FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
NICKEL	.600E+01	.252E+01	.590E+02	.500E-01	N.0 E+00
COBALT	.300E+01	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
IRON	>.100E+04	>.697E+03	.110E+02	.199E+01	N.0 E+00
MANGANESE	>.100E+04	>.354E+02	.400E+00	.290E-01	N.0 E+00
CHROMIUM	.800E+01	.791E+00	.300E+01	.160E-01	N.0 E+00
VANADIUM	.290E+02	.216E+00	.0 E+00	.300E-02	N.0 E+00
TITANIUM	>.100E+04	.0 E+00	.0 E+00	.360E+00	N.0 E+00
SCANDIUM	.900E+00	.0 E+00	.0 E+00	.0 E+00	N.0 E+00
CALCIUM	>.100E+04	U.0 E+00	.143E+03	.350E+01	N.0 E+00
POTASSIUM	>.100E+04	>.388E+02	.106E+03	>.990E+01	N.0 E+00
CHLORINE	.880E+03	.165E+02	.0 E+00	.0 E+00	N.0 E+00
SULFUR	>.100E+04	>.194E+02	.100E+01	>.490E+01	N.0 E+00
PHOSPHORUS	>.100E+04	>.137E+03	.0 E+00	.0 E+00	N.0 E+00
SILICON	>.100E+04	U.0 E+00	.0 E+00	>.940E+01	N.0 E+00
ALUMINUM	>.100E+04	U.0 E+00	.110E+02	>.760E+00	N.0 E+00
MAGNESIUM	>.100E+04	U.0 E+00	.200E+01	.870E+00	N.0 E+00
SODIUM	>.100E+04	U.0 E+00	.800E+01	>.140E+01	N.0 E+00
FLUORINE	.550E+02	.0 E+00	.260E+01	.230E+01	N.0 E+00
BORON	.150E+03	.0 E+00	.0 E+00	.100E-02	N.0 E+00
BERYLLIUM	.300E+00	<.719E-01	.0 E+00	.0 E+00	N.0 E+00
LITHIUM	.220E+02	.359E+00	.0 E+00	.0 E+00	N.0 E+00

ETHAN ALLEN
TEST 2 - WET WOOD

PPM

ELEMENT	FUEL : WET WOOD	FLYASH
URANIUM	.0 E+00	.100E+01
THORIUM	.0 E+00	.600E+01
BISMUTH	.0 E+00	.0 E+00
LEAD	.300E+00	.610E+02
THALLIUM	.400E-01	.0 E+00
MERCURY	<.500E-01	<.500E-01
PLATINUM	.0 E+00	.0 E+00
TUNGSTEN	.0 E+00	.700E+00
TANTALUM	.0 E+00	N.0 E+00
HAFNIUM	.800E-01	.700E+00
LUTETIUM	.0 E+00	.0 E+00
YTTERBIUM	.0 E+00	.800E+00
THULIUM	.0 E+00	.100E+00
ERBIUM	.0 E+00	.600E+00
HOLMIUM	.0 E+00	.200E+01
DYSPROSIUM	.0 E+00	.300E+01
TERBIUM	.0 E+00	.100E+01
GADOLINIUM	.0 E+00	.400E+01
EUROPIUM	.0 E+00	.800E+00
SAMARIUM	.0 E+00	.600E+01
NEODYMIUM	.200E-01	.400E+01
PRASEODYMIUM	.400E-01	.600E+01
CERIUM	.200E+00	.350E+02
LANTHANUM	.200E+00	.350E+02
BARIUM	.360E+02	>.100E+04
CESIUM	.300E-01	.900E+00
IODINE	.400E-01	.300E+01
TELLURIUM	.500E-01	.400E+00
ANTIMONY	N.0 E+00	N.0 E+00
TIN	.300E-01	.200E+00
CADMIUM	.100E+00	.100E+01
SILVER	.800E-01	<.200E+00
MOLYBDENUM	.700E-01	.700E+00
NIOBIUM	.100E+00	.700E+01
ZIRCONIUM	.500E+00	.390E+02
YTTRIUM	.600E-01	.200E+02
STRONTIUM	.120E+02	.860E+03
RUBIDIUM	.300E+01	.290E+03
BROMINE	.700E-01	.290E+02
SELENIUM	<.200E-01	.400E+01
ARSENIC	N.0 E+00	N.0 E+00
GERMANIUM	<.100E-01	.800E+00
GALLIUM	.100E+00	.110E+02
ZINC	.220E+02	.390E+03
COPPER	.300E+01	.450E+02

ETHAN ALLEN
TEST 2 - WET WOOD
PPM

PPM

ELEMENT	FUEL : WET WOOD	FLYASH
NICKEL	.300E+00	.140E+02
COBALT	.500E+00	.300E+01
IRON	>.100E+03	>.100E+04
MANGANESE	>.760E+02	>.100E+04
CHROMIUM	.400E-01	.380E+02
VANADIUM	.600E+00	.250E+02
TITANIUM	.900E+01	>.100E+04
SCANDIUM	.100E-01	.800E+00
CALCIUM	>.100E+03	>.100E+04
POTASSIUM	>.920E+02	>.100E+04
CHLORINE	.400E+01	.190E+03
SULFUR	>.470E+02	.280E+03
PHOSPHORUS	>.100E+03	>.100E+04
SILICON	>.100E+03	>.100E+04
ALUMINUM	>.700E+01	>.100E+04
MAGNESIUM	>.100E+03	>.100E+04
SODIUM	>.190E+02	>.100E+04
FLUORINE	.700E+01	.100E+03
BORON	.300E-01	.130E+02
BERYLLIUM	<.100E-01	<.100E+00
LITHIUM	.500E-01	.200E+01

ETHAN ALLEN
TEST 2 - WET WOOD

CONCENTRATION ELEMENT	MCG/DSCM 10U + 3U CYCLONES	1U + FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
URANIUM	.528E+00	.117E-01	.0 E+00	.0 E+00	N .0 E+00
THORIUM	.792E+00	.117E-01	.0 E+00	.0 E+00	N .0 E+00
BISMUTH	.792E-01	.234E-01	.0 E+00	.0 E+00	N .0 E+00
LEAD	.166E+02	.934E+00	.0 E+00	.343E+00	N .0 E+00
THALLIUM	.0 E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
MERCURY	< .300E+00	< .584E-01	< .202E+00	< .685E-01	< .495E-01
PLATINUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
TUNGSTEN	.0 E+00	.292E-01	.0 E+00	.0 E+00	N .0 E+00
TANTALUM	.0 E+00	< .584E-02	.0 E+00	.0 E+00	.0 E+00
HAFNIUM	.528E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
LUTETIUM	.528E-01	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
YTTERBIUM	.528E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
THULIUM	.528E-01	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
ERBIUM	.158E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
HOLMIUM	.211E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
DYSPROSIUM	.792E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
TERBIUM	.185E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
GADOLINIUM	.528E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
EUROPIUM	.185E+00	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
SAMARIUM	.792E+00	.234E-01	.0 E+00	.0 E+00	N .0 E+00
NEODYMIUM	.106E+01	.234E-01	.0 E+00	.441E+00	N .0 E+00
PRASEODYMIUM	.211E+01	.584E-02	.0 E+00	.979E-01	N .0 E+00
CERIUM	.108E+02	.175E-01	.0 E+00	.245E+00	N .0 E+00
LANTHANUM	.190E+02	.701E-01	.0 E+00	.294E+00	N .0 E+00
BARIUM	> .264E+03	> .578E+02	.144E+01	.940E+01	N .0 E+00
CESIUM	.264E+00	< .584E-02	.0 E+00	< .490E-01	N .0 E+00
IODINE	.264E+00	.584E-02	.0 E+00	.0 E+00	N .0 E+00
TELLURIUM	.0 E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
ANTIMONY	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	< .495E+00
TIN	.264E+00	.175E-01	.0 E+00	.245E+01	N .0 E+00
CADMIUM	.792E+00	.117E-01	.0 E+00	.490E-01	N .0 E+00
SILVER	< .264E+00	.117E+00	.913E+01	.490E+01	N .0 E+00
MOLYBDENUM	.106E+01	.234E-01	.288E+01	.490E-01	N .0 E+00
NIOBIUM	.158E+01	.0 E+00	.0 E+00	.441E+00	N .0 E+00
ZIRCONIUM	.581E+01	.584E-01	.144E+01	.441E+00	N .0 E+00
YTTRIUM	.343E+01	.584E-02	.0 E+00	.490E-01	N .0 E+00
STRONTIUM	> .264E+03	.455E+01	.480E+00	.142E+01	N .0 E+00
RUBIDIUM	.792E+02	.175E+01	.0 E+00	.979E+00	N .0 E+00
BROMINE	.370E+01	.0 E+00	.817E+01	.0 E+00	N .0 E+00
SELENIUM	.528E+00	.584E-01	.0 E+00	.490E+00	N .0 E+00
ARSENIC	N .0 E+00	N .0 E+00	N .0 E+00	N .0 E+00	< .495E+00
GERMANIUM	.106E+00	.584E-02	.0 E+00	.0 E+00	N .0 E+00
GALLIUM	.132E+01	.409E-01	.0 E+00	.294E+00	N .0 E+00
ZINC	.121E+03	.346E+02	.106E+03	.881E+01	N .0 E+00
COPPER	.222E+02	.111E+01	.336E+02	.220E+01	N .0 E+00

ETHAN ALLEN
TEST 2 - WET WOOD

CONCENTRATION MCG/DSCM

ELEMENT	10U + 3U CYCLONES	1U + FILTER	XAD-2	1ST IMPINGER	2ND & 3RD IMPINGERS
NICKEL	.158E+01	.204E+00	.283E+03	.245E+01	N .0 E+00
COBALT	.792E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
IRON	> .264E+03	> .566E+02	.528E+02	.974E+02	N .0 E+00
MANGANESE	> .264E+03	> .288E+01	.192E+01	.142E+01	N .0 E+00
CHROMIUM	.211E+01	.642E-01	.144E+02	.783E+00	N .0 E+00
VANADIUM	.766E+01	.175E-01	.0 E+00	.147E+00	N .0 E+00
TITANIUM	> .264E+03	.0 E+00	.0 E+00	.176E+02	N .0 E+00
SCANDIUM	.238E+00	.0 E+00	.0 E+00	.0 E+00	N .0 E+00
CALCIUM	> .264E+03	U .0 E+00	.687E+03	.171E+03	N .0 E+00
POTASSIUM	> .264E+03	> .315E+01	.509E+03	> .485E+03	N .0 E+00
CHLORINE	.232E+03	.134E+01	.0 E+00	.0 E+00	N .0 E+00
SULFUR	> .264E+03	> .158E+01	.480E+01	> .240E+03	N .0 E+00
PHOSPHORUS	> .264E+03	> .111E+02	.0 E+00	.0 E+00	N .0 E+00
SILICON	> .264E+03	U .0 E+00	.0 E+00	> .460E+03	N .0 E+00
ALUMINUM	> .264E+03	U .0 E+00	.528E+02	> .372E+02	N .0 E+00
MAGNESIUM	> .264E+03	U .0 E+00	.961E+01	.426E+02	N .0 E+00
SODIUM	> .264E+03	U .0 E+00	.384E+02	> .685E+02	N .0 E+00
FLUORINE	.145E+02	.0 E+00	.125E+02	.113E+03	N .0 E+00
BORON	.396E+02	.0 E+00	.0 E+00	.490E-01	N .0 E+00
BERYLLIUM	.792E-01	< .584E-02	.0 E+00	.0 E+00	N .0 E+00
LITHIUM	.581E+01	.292E-01	.0 E+00	.0 E+00	N .0 E+00

CONCENTRATION	ETHAN ALLEN TEST 2 - WET WOOD MCG/DSCM
ELEMENT	STACK EXHAUST
URANIUM	.540E+00
THORIUM	.804E+00
BISMUTH	.103E+00
LEAD	.179E+02
THALLIUM	< .584E-02
MERCURY	< .678E+00
PLATINUM	.0 E+00
TUNGSTEN	.292E-01
TANTALUM	< .584E-02
HAFNIUM	.528E+00<X<.534E+00
LUTETIUM	.528E-01<X<.586E-01
YTTERBIUM	.528E+00<X<.534E+00
THULIUM	.528E-01<X<.586E-01
ERBIUM	.158E+00<X<.164E+00
HOLMIUM	.211E+00<X<.217E+00
DYSPROSIUM	.798E+00
TERBIUM	.185E+00<X<.191E+00
GADOLINIUM	.528E+00<X<.534E+00
EUROPIUM	.185E+00<X<.191E+00
SAMARIUM	.815E+00
NEODYMIUM	.152E+01
PRASEODYMIUM	.222E+01
CERIUM	.111E+02
LANTHANUM	.194E+02
BARIUM	> .333E+03
CESIUM	.264E+00<X<.319E+00
IODINE	.270E+00
TELLURIUM	.0 E+00
ANTIMONY	< .495E+00
TIN	.273E+01
CADMIUM	.853E+00
SILVER	.141E+02<X<.144E+02
MOLYBDENUM	.401E+01
NIOBIUM	.202E+01
ZIRCONIUM	.775E+01
YTTRIUM	.349E+01
STRONTIUM	> .270E+03
RUBIDIUM	.819E+02
BROMINE	.119E+02
SELENIUM	.108E+01
ARSENIC	< .495E+00
GERMANIUM	.111E+00
GALLIUM	.165E+01
ZINC	.270E+03
COPPER	.591E+02

CONCENTRATION	ETHAN ALLEN TEST 2 - WET WOOD MCG/DSCM
ELEMENT	STACK EXHAUST
NICKEL	.288E+03
COBALT	.792E+00
IRON	> .471E+03
MANGANESE	> .270E+03
CHROMIUM	.174E+02
VANADIUM	.782E+01
TITANIUM	> .282E+03
SCANDIUM	.238E+00
CALCIUM	> .112E+04
POTASSIUM	> .126E+04
CHLORINE	.234E+03
SULFUR	> .510E+03
PHOSPHORUS	> .275E+03
SILICON	> .724E+03
ALUMINUM	> .354E+03
MAGNESIUM	> .316E+03
SODIUM	> .371E+03
FLUORINE	.140E+03
BORON	.397E+02
BERYLLIUM	.792E-01<X<.850E-01
LITHIUM	.584E+01